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Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation (CALIPSO) Spacecraft

Independent Technical Assessment

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June 2004

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Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite Observation (CALIPSO) Spacecraft

Independent Technical Assessment

Performed by

The NASA Engineering and Safety Center (NESC)

January 27, 2004

Report of the ITA Findings to the NESC

1 Identification

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Short Title: CALIPSO Spacecraft Proteus Propulsion System Assessment	
Description: Personnel hazards associated with Proteus Hydrazine propulsion bus once loaded (launch-36 days)	
Date Received: 10-22-03	Date ITA/I Initiated: 11-06-03
NESC Chief Engineer (NCE) Assigned: Michael Hagopian	NCE Contact Info: 301-286-6732
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Date ITA/I Concluded: 1-27-04	

2 Executive Summary

The CALIPSO spacecraft is scheduled for launch on a Boeing Delta II rocket from Space Launch Complex-2 (SLC-2) at Vandenberg Air Force Base (VAFB) in 2005. CALIPSO uses an “off the shelf” hydrazine-fueled Proteus propulsion bus manufactured by Alcatel Space Industries. The bus is provided by the Centre National d'Etudes Spatiales (CNES) as part of its in-kind contribution to the joint mission. While an identical bus was flown in 2001 on the Jason-1 spacecraft, concerns have been raised by GSFC safety and engineering that the Proteus bus does not meet NASA fault tolerance design guidelines[1] or all of the Air Force Eastern and Western Range (EWR) requirements[2], thus posing an unacceptable hazard to processing personnel. The Air Force EWR, Kennedy Space Center (KSC) Expendable Launch Vehicle Office, and Langley Research Center (LaRC) are all in agreement that the spacecraft is safe to process and launch given the planned spacecraft integrity testing and operational controls in place. GSFC believes the risks from these potential events have been incorrectly classified and has recommended additional measures to mitigate personnel hazards assuming the undesired events will occur.

The scope of this effort was a review of the Proteus propulsion bus design and an assessment of the potential for personnel exposure to hydrazine propellant. Loss of mission, spacecraft or launch facilities is obviously an undesired outcome, but was purposely placed outside the scope of this assessment. The duration of this assessment was two months. Specifically reviewed were the potential for leakage from the five (5) mechanical fittings on the Proteus bus, potential leakage through the thruster valves and the potential for an inadvertent firing of the thrusters. These personnel hazards exist only during the period when the system is filled and pressurized until launch (approximately 36 days). Material from a variety of sources was reviewed and a site visit was made to VAFB to review the payload processing facilities and Delta II pad where CALIPSO will be processed and launched. It should be noted that key CNES information requested for this assessment through the GSFC program office was not provided (ref. Appendix A). This fact limited the review team's ability to draw conclusions based on objective evidence and formed the basis for many of the requirements.

The NESC acknowledges that welded joints are superior to mechanical fittings in preventing leakage but attention to workmanship and proper verification of the joint integrity is required for both. Mechanical fittings do afford a greater degree of flexibility in the assembly and repair of tubing systems. However, a thorough risk assessment must be conducted early in the design process to arrive at a configuration that presents the overall minimum risk to personnel, the mission and the environment. During the course of the review it was noted that the hydrazine system does not have a tank isolation valve. The NESC team acknowledges that the omission of a tank isolation valve in the propulsion feed system is less safe during ground operations than a system that has the capability to isolate leaks; but while one may be safer, both can be made safe through proper hardware development and launch site processes. Again, a thorough risk assessment must be performed when designing the spacecraft to make these configuration decisions.

At this time, the NESC cannot objectively conclude that the Proteus bus as designed poses either acceptable or unacceptable risk to personnel. The program must adequately address all eleven (11) requirements stated in this report before the NESC can conclude personnel risk is acceptable. The requirements call for program review and approval of CNES assembly and acceptance test procedures and verification that the planned acceptance testing and integrity checks are performed by CNES before hydrazine is loaded into the system. Further, verification of the planned operational controls (e.g., leak detection, alarms, installation of the thruster arm plugs, personnel controls and minimizing spacecraft operations once loaded) are required to mitigate the risks to an acceptable level. Compatibility of hydrazine with the Voi-Shan nickel conical seals will be determined through an ongoing series of tests being conducted by Aerojet and test results will be documented in an addendum to this report.

3 Detailed Description of the Problem

CALIPSO is a joint science mission between the CNES, LaRC and GSFC. It was selected as an Earth System Science Pathfinder satellite mission in December 1998 to address the role of clouds and aerosols in the Earth's radiation budget. The spacecraft includes a NASA light detecting and ranging (LIDAR) instrument, a NASA wide-field camera and a CNES imaging infrared radiometer.

The issues addressed in this assessment involve the Proteus spacecraft bus provided to CNES via subcontract with Alcatel Space Industries. This bus is identical to that flown on the Jason-1 mission launched in December 2001 on a Delta II from VAFB. NASA's Jet Propulsion Lab managed the Jason-1 mission. Issues on CALIPSO are associated with the Proteus hydrazine propulsion system used for orbit corrections depicted in Figure 1. The system has five (5) mechanical MS-33656 37° Army/Navy (A/N) fittings, one located at each of the four (4) 0.225 pound-force thrusters (Astrium model CHT 1N) and one at the outlet of the ten (10) gallon hydrazine tank manufactured by Rafael. All other connections in the hydrazine system are welded.

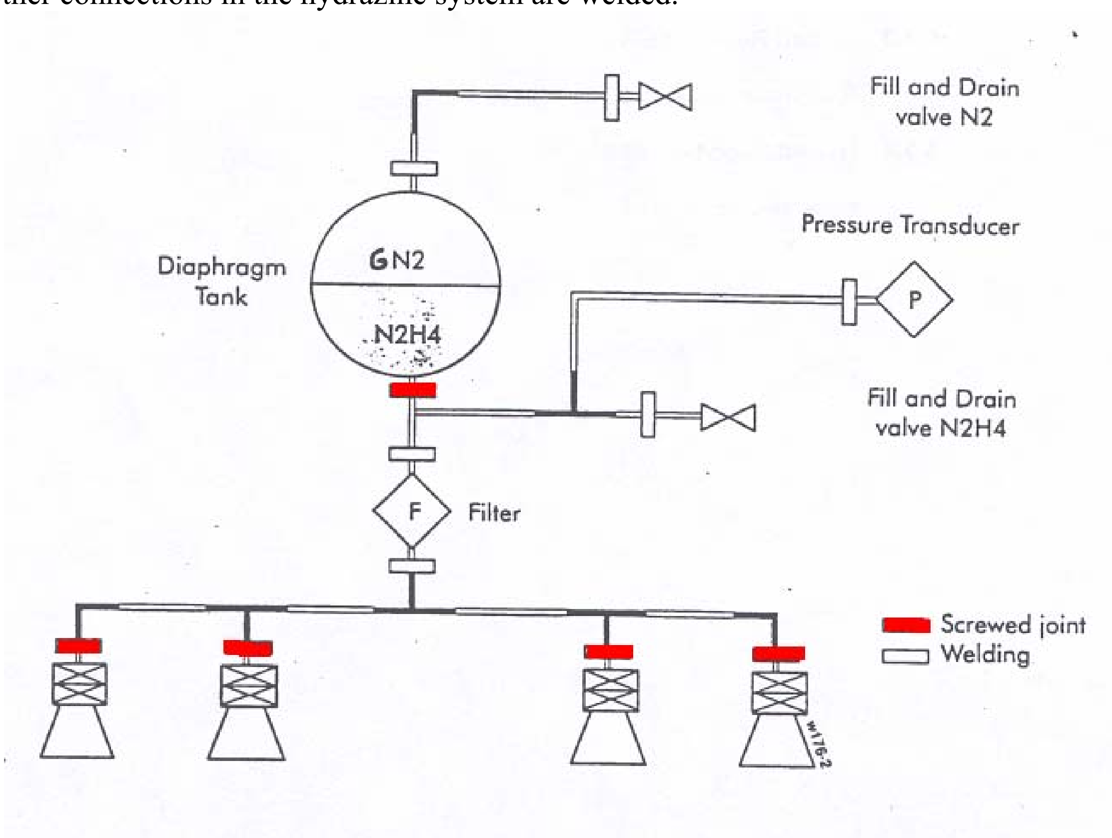

Figure 1. Schematic of CALIPSO Propulsion System

Three key issues have been highlighted: (1) use of mechanical fittings instead of welded joints for propulsion system fluid connections, (2) the potential for hydrazine leakage through thrusters and (3) the potential for inadvertent thruster firing. Personnel risks associated with these issues are:

- Toxic exposure to hydrazine leakage from the mechanical fittings
- Toxic exposure to un-reacted hydrazine in the thruster exhaust via leakage through the thruster valves or inadvertent thruster firing
- Fire potential from hydrazine leakage and subsequent contact with incompatible spacecraft materials
- Fire potential from thruster hot gas exhaust igniting combustible spacecraft materials

4 Causal Factors

NESC focused on the three key issues as stated above. A detailed assessment of the causal factors that could potentially lead to a catastrophic event can be found in the NESC-developed fault tree (ref. Appendix B). A more general discussion follows.

Leakage through the mechanical fitting can be influenced by a number of design, environmental, assembly and processing factors. The design of the fitting must provide a consistent clamping force sufficient to provide sealing integrity in the environment to which it will be exposed. Key design factors include adequacy of structural/mechanical design margins and compatibility of material selections of the various A/N fitting components. Environmental factors that could influence leakage include temperature, pressure, vibration and shock. The environmental factors must consider the flight mission as well as those induced during spacecraft transportation and during ground processing. Assembly and processing factors that must be considered include proper torque application, potential for the introduction of contamination in the assembly and potential damage induced during assembly. A comprehensive qualification and acceptance test program can both certify the design for these conditions and verify the adequacy of the assembly process.

Leakage through the thruster can also be influenced by a number of design, environmental, assembly and processing factors. Flow control valves located upstream of each thruster physically control propellant flow to the thruster catalyst bed. Key design factors for the valve include adequacy of structural/mechanical design margins and compatibility of material selected for the valve components. A number of environmental factors can influence the performance of the valve and its propensity for leakage. They include temperature, pressure, vibration and shock, and must be considered for both the flight mission as well as those induced during spacecraft transportation and ground processing. Risk of leakage through the flow control valves can be significantly reduced with a comprehensive qualification and acceptance test program by certifying the design and verifying the adequacy of the assembly process.

An inadvertent thruster firing could be initiated by unintentionally applying power to the actuation circuit, the drivers or the valve solenoids. The power source could be from the Ground Support Equipment (GSE) or an internal short in the spacecraft electronics. One additional influencing factor could be an inadvertent ON command by the spacecraft or GSE software. Typical safeguards used to minimize the potential for inadvertent thruster firing includes redundancy in the design which would require multiple failures to apply power and designs having multiple inhibits to prevent inadvertent application of power.

5 NESC Risk Assessment

5.1 Overview

Anhydrous hydrazine (N_2H_4) is a colorless, oily, flammable liquid that is miscible with water. It has a penetrating odor resembling that of ammonia with an odor threshold of 3.7 parts per million (ppm). The National Institute of Occupational Safety and Health's immediately dangerous to life or health (NIOSH IDLH) limit is set at 50 ppm[3]. This is the recommended exposure limit to ensure that a worker can escape from an exposure condition that is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from the environment. The Occupational Safety and Health Administration permissible exposure limit (OSHA PEL) for hydrazine is 1 ppm[4]. This is expressed as a time-weighted average and is the concentration of a substance to which most workers can be exposed without adverse effect averaged over a normal 8-hour workday or a 40-hour workweek. The American Conference of Governmental and Industrial Hygienists' threshold limit value (ACGIH TLV) is 0.01 ppm[5] and is expressed as a time-weighted average; the concentration of a substance to which most workers can be exposed without adverse effects. It should be noted that OSHA numbers are regulatory, whereas NIOSH and ACGIH numbers are advisory. NASA and the Air Force use the more stringent time-weighted TLV of 0.01 ppm as the limit for worker exposure[6].

Hydrazine liquid is extremely reactive and contact with incompatible materials can spur spontaneous combustion resulting in a fire. The explosive range of hydrazine in air is between 4.7 and 99 percent. Although hydrazine is detonable above concentrations of

4.7 percent in air, its low vapor pressure of 0.27 pounds per square inch absolute makes it more difficult to build up sufficient concentrations in a well-ventilated area[7].

The fact a hazardous event is unlikely to occur does not mean it *cannot* occur. For the three fault tree events considered in Appendix B (leakage of the mechanical fittings, leakage through the thruster valves and inadvertent firing of the thruster) a wide range of probabilities were derived by the GSFC and LaRC safety offices along with differing opinions on severity. There is subjectivity in determining an event probability as evidenced by the wide spread between the two safety offices. It was not feasible for the NESC to better quantify the probabilities through specific testing or analysis in the timeframe given. Hydrazine is a hazardous commodity and in the NESC assessment team's judgment, the possibility of leakage does exist and the event severity is catastrophic to personnel. Given this premise, the focus of this assessment was to minimize the probability that the current design could initiate these undesired events and ensure operational controls are in place to maximize personnel safety.

5.2 Fault Tree Analysis and Mitigation

The CALIPSO fault tree (Appendix B) and mitigation table (Appendix C) were developed to identify all possible initiators leading to the three events and provide mitigation rationale for these events. The methods of verification specified by NASA system safety standards are inspection, test, analysis, demonstration and similarity. However, for this assessment, demonstration ("We flew it before") and similarity ("It worked on Jason-1") were not used as a means of closing fault tree events. Specifically, closeout of fault tree events could not be made due to the lack of availability of assembly level procedures and specifications. Events that could not be closed were incorporated into the NESC requirements.

6 Overview of the Initial ITA Plan

NESC reviewed the Proteus propulsion system design to assess the potential for personnel exposure to hydrazine from mechanical fittings or thrusters as well as the potential for inadvertent thruster firing. This assessment focused only on hazards present from the time the propulsion system is filled with hydrazine and pressurized to final closeout for launch, a period of about 36 days. Suitability of the system for flight and the potential for damage to flight hardware or launch facilities during ground processing were considered program risks and were not addressed. Likewise, this assessment did not address workmanship issues. It was assumed that stamp warranties, training, and process controls were properly implemented, hardware was built to print and work tasks were complete as documented.

Fault trees for each of the potential failures under assessment were developed as presented in Appendix B. Credible failure modes were identified and the controls the CALIPSO program has placed on those failures assessed. For failures the program has not already assessed or for which controls were deemed inadequate, independent testing was conducted to validate the program's approach or additional controls were recommended.

7 Modifications to the ITA Plan

While decisions to incorporate or eliminate certain tests were made as the assessment matured, the basic ITA approach outlined above remained unchanged. Initially, NESC planned to build a flight fidelity mockup of the hydrazine tank, tubing and thruster setup to perform leak and vibration testing. After NESC requests for accurate configuration drawings were denied to the program by CNES, the value of the vibration testing was deemed questionable and dropped. A separate issue arose when conflicting data on the compatibility of hydrazine with the nickel seal in the A/N fitting was discovered. Compatibility tests, consultation with material compatibility experts and a literature search were added. Information from NASA's White Sands Test Facility (WSTF) surfaced during final report preparation that resulted in the addition of a 36 day room temperature nickel seal soak test with results to be supplied as an addendum (see Section 9.1.2 for details).

8 ITA Team

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9 ITA Identified Alternative Courses of Action

9.1.0 – Mechanical Fitting Leakage

Properly welded fluid connections are inherently more reliable than mechanical fittings and should be incorporated in fluid propulsion system designs when possible. There are some circumstances, however, under which mechanical fittings offer an appropriate design solution. Ready interface to off-the-shelf parts, ease of maintenance, or potential for damage to soft goods during welding all may dictate use of threaded joints. MS-33656 type 37° A/N-fittings have been employed successfully in aerospace applications for many years and are acceptable for limited use providing they are (1) properly assembled, (2) validated by leak check as an assembly before use, (3) exposed only to temperature, pressure, vibration and shock environments for which they are certified, and (4) incorporate a secondary locking feature. The Proteus bus uses five such fittings; one at the hydrazine tank outlet and one at each of the thruster inlets (see Figures 2 and 3 for details). While lock-wire is used as a secondary locking feature, it is suitable only for preventing significant rotation of the B-nut and full disengagement of the fitting. Lock-wire alone will not prevent loss of joint preload[8] with subsequent reduction of clamping force at the sealing surfaces, and thus cannot be counted upon to prevent a fitting from leaking.

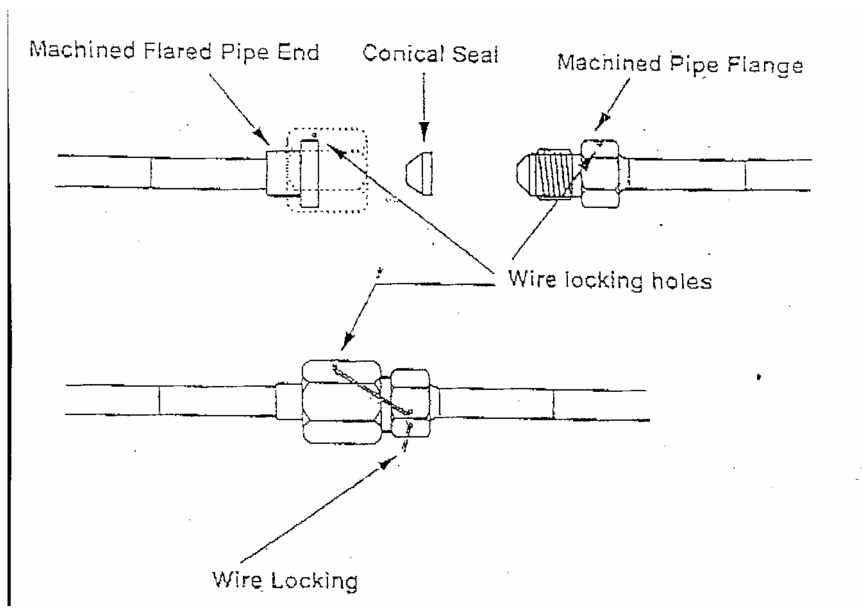

Figure 2. MS 33656 A/N fitting installation detail

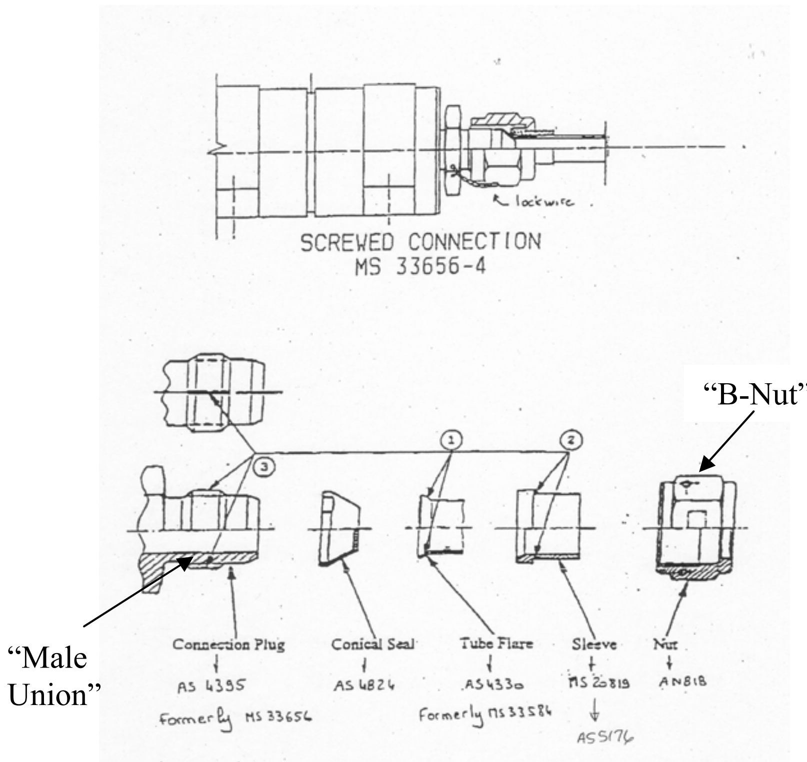

Figure 3. Exploded view of MS-33656-4 Fitting

While the NESC was not provided specific qualification and acceptance test data for the CALIPSO Proteus bus, the NESC reviewed relevant test data from other propulsion system and component tests. In general these tests addressed qualification, acceptance and sensitivity of the MS-33656 type 37° A/N fittings for exposure to the environmental conditions of temperature, pressure, vibration, shock and assembly cycles. The following sections of this report summarize three test series conducted on the MS-33656 threaded fitting and the mitigating actions required to assure integrity of the CALIPSO Proteus bus fittings.

9.1.0.0 – Review Voi-Shan Results of Evaluation Tests Conducted on Voi-Shan Conical Seals[9]

The objective of this test program was to demonstrate that the Voi-Shan conical seal would consistently seal a flared A/N fitting tube connection under varying applications. The test conditions were established in order to simulate very stringent requirements that could be encountered in actual usage. The environmental exposure conditions used in this test series are similar to the requirements for the CALIPSO spacecraft and in many cases bound them.

The test series used various sizes of the A/N 815 (fitting end, superceded by MS 33656, currently AS 4395), A/N 818 and A/N 819 (sleeve, superceded by MS 20819, currently AS5176), fittings and conical seals made in accordance with Voi-Shan standard VSF 1015 manufactured from aluminum, copper, tin and nickel. Test conditions included:

1. Pressure at room temperature of 1500–4500 pounds per square inch gage (psig) induced with helium, air and nitrogen and 6000 psig induced with hydraulic fluid
2. Pressure at elevated temperature: 500 °F at 3000 psig-air
3. Pressure testing during repeated disassembly/assembly: 1500 psig for 20 cycles and 300 psig for 30 cycles
4. Sine sweep vibration testing with 3000 psig pressure
5. Torque relaxation combined with time (6 to 360 hours), pressure cycling and vibration
6. Shock testing: 20g's shock at 3000 psig helium, and 100 g's shock at 3000 psig water
7. Thermal Shock at 200 ºF and 1500 psig-helium
8. Pressure Impulse testing from 0-4500 psig at 35 cycles per minute for 100 cycles

Several measurement techniques were used to measure leak rate depending on the tests being conducted. They included submersion in water or benzene, using a helium sensitive mass spectrometer, a visual inspection if liquids were being used as the pressure medium and pressure decay over time. Torque relaxation was measured by applying torque in the tightening direction and measuring the angle required to achieve to the original torque value.

The published results show a robust design for all of the configurations tested within the conditions specified. Test results indicated that all of the joints remained sealed with no leakage measured. The torque relaxation tests did show some relaxation over time and after exposure to pressure cycles. In the pressure cycle testing the largest change in torque was 27% and this occurred after the first pressure cycle. Torque relaxation reduced to no relaxation after the third cycle and only showed 13% relaxation after the second cycle worst case. Results of vibration tests showed no torque loss after exposure to vibration. The assembly, checkout and acceptance testing processes conducted on the CALIPSO Proteus bus can mitigate the two conditions (time and exposure to pressure) that did show some torque loss sensitivity.

9.1.0.1 – Review of European Retrievable Carrier (EURECA) Spacecraft Qualification Test Report for the ENN 51200 – Size 4 Joint for High Pressure Application[10]

The objective of this test program was to qualify the design of ENN 51200 E joint (MS-33656 flared tube connection) for the use in EURECA program for high-pressure applications. Qualification environments that the high-pressure joint was required to withstand include loads induced from the vibration environment, thermal environment, operational pressure and pressure cycling, mounting (assembly torque) activities, proof pressure and burst pressure. The environmental exposure conditions used in this test series are similar to the requirements for the CALIPSO spacecraft. Three configurations of tubing length combined with the MS-33656 fittings were included in the test series to represent different load influencing factors. These include an angle length configuration to induce torsion and bending on the fitting, a torsion lever configuration to induce torsion on the fitting, and a straight tube length to induce axial loads on the fitting during the thermal testing. Leak checks were performed pre and post exposure to the loading conditions. The setup for leak testing included a vacuum test chamber, the test article, a helium leak detector, a vacuum pump and a helium pressure supply. The external leak rate criteria indicated failure if it exceeded $1x10^{-6}$ standard cubic centimeters per second (scc/sec).

The published results of the test series indicated that there were no leak rate failures experienced for any of the three test configurations subjected to all of the loading conditions. The test report also emphasized that the loads induced by vibration in particular did not result in developing an external leak.

9.1.0.2 – Review of Experiments on the Robustness of Separable Fittings[11]

The objective of this test program was to investigate the effect of off nominal or stressing conditions on various mechanical fittings to assess the likelihood of leakage. Stressing conditions used in the test series included vibration (30 g's root mean square for 300 sec), thermal stress (exposure to cryogenic temperature), misalignment (2 degree offset), under-torque (50 % of nominal), and assembly in the presence of foreign debris (scoring of the sealing surface). The ½ inch size A/N fitting was one of four types being evaluated in the test series. Other types include a Dynatube fitting (beam seal tubing connector), a KC fitting (a modified A/N fitting with Teflon gasket), and a Swagelok fitting. Two test series were performed; one test series subjecting each fitting to various combinations of the stressing conditions and a second test series based on an eight row Taguchi matrix of conditions with the four fitting used in the first series plus one additional fitting called the GE fitting (A/N modified with a radiused or ball nose). Conditions for the second test series had also been modified based on results of the first test showing insensitivity to some of the stressing conditions. The second test series has not been reported at this time so the following discussion is based on significant findings from the first test series.

Preliminary results of the first series of tests showed a wide variability of the various fitting responses to off-nominal conditions and identified some insensitivities that are relevant to the CALIPSO assessment. Even though these tests cannot explicitly quantify the integrity of the ¼ inch A/N fitting in the CALIPSO Proteus bus, data from these tests does show insensitivity or an inherent robustness of the A/N type fitting to some of the relevant causal factors associated with the hydrazine leak potential. It was determined that vibration and misalignment were not significant factors in the probability of leaks in the separable fittings as results showed negligible effect on the sealing qualities of the fittings. Surprisingly, the test series showed that vibration tended, if anything, to reduce leak rates more often than it increased them. In no case did a previously non-leaking fitting start to leak as a result of vibration and in 13 cases having the under-torque condition with a measurable leak rate, 10 had reduced leak rates after vibration. The two under-torqued A/N fittings with the largest pre-vibration leak rate had an increase in leak rate post vibration. With regard to misalignment, it was reported that the fittings appear to be sufficiently robust to withstand two degrees of misalignment prior to assembly. It was also reported that fittings that performed the most poorly were most sensitive to under-torque and contamination (scoring of the surface). Both the A/N and Swagelok fittings appeared to be sensitive to under-torque and surface scratches. However, appropriate inspection and assembly procedures and post-assembly acceptance testing can mitigate both of these sensitivities.

9.1.0.3 – Summary of Historical Data Review

MS-33656 threaded couplings show an inherent robustness if properly assembled, acceptance tested, leak checked and other appropriate checkouts are performed. Even though these test series do not constitute a qualification of these threaded fittings, they certainly demonstrate that the MS-33656 threaded coupling design provides adequate sealing integrity for the types of environments that the CALIPSO Proteus bus could be exposed to during its processing and flight mission.

9.1.1 – CALIPSO Proteus Bus Fitting Assembly

The torque level indicated by a gauge or wrench during fitting assembly does not represent actual clamping force at the sealing surface. In some cases, clamping force may not be sufficient to effectively seal a fitting, even though the B-nut is torqued to the specified level. Thread binding or physical interference with the wrench head can result in such a “false torque” condition. Mechanical fittings must be lubricated slightly to prevent galling and minimize the possibility of false torque. Quantity and location of lubricant must be controlled to ensure not only that it is applied but also that it is applied only to moving parts and not to a sealing surface. Lube on a sealing surface may fill a scratch or other discrepancy allowing a fitting to pass leak check, only to be washed away or dissolved in the presence of liquid propellant creating a void that leads to a leak. CNES has indicated that lubricants were used in the assembly of the Proteus bus, but NESC was not provided copies of assembly procedures or specific data to indicate where, or in what quantities the lubricants were applied.

As an overarching statement, any procedure review or procedure development done in response to the following eleven (11) NESC requirements should consider not only engineering content but also the clarity or "workability" of the procedure from a human factors perspective. That is, care should be taken to ensure the procedures clearly convey the author's intent without ambiguity that could confuse the operator and lead to an unintended outcome.

NESC-R-001 - Program shall demonstrate that Alcatel training and/or assembly documentation provided for proper lubrication of fluid fittings during assembly. Assembly procedures shall clearly delineate the type, quantity and location where lubricant was applied and ensure sealing surfaces were kept dry and free of any contaminant.

Fittings must be visually inspected before assembly to ensure no discrepant condition exists that might lead to leakage. Damaged threads, burrs or machining marks may cause galling and subsequent false torque. A contaminant on a sealing surface may not be detected during leak checks, but be washed away or dissolved in the presence of liquid propellant creating a void that leads to a leak. NESC was not provided copies of assembly procedures documenting Proteus bus pre-assembly inspections.

NESC-R-002 – Program shall demonstrate that Alcatel training and/or assembly documentation provided for a visual inspection of fluid fittings prior to assembly. Assembly procedures shall ensure components had no visible defects and sealing surfaces were clean and dry.

9.1.2 – Material Compatibility

Fault tree assessment highlighted the potential for component failure as a result of material incompatibility. There was some conflict among the various sources consulted concerning the compatibility of nickel used in the MS-33656 fitting conical seals and hydrazine[12,13,14,15]. Materials experts at WSTF were consulted who indicated that decomposition of hydrazine when exposed to nickel is accelerated at temperatures above 212 °F[16] but the small amount of surface area exposed in this application was insignificant to make decomposition a concern. The possibility of corrosion exists in the long-term, but it should not lead to leakage resulting in personnel exposure in the 36-day period under assessment. The fact Voi-Shan seals are not plated is also favorable in this regard. However, since there were some lingering questions regarding compatibility and no evidence Alcatel conducted any definitive testing before incorporating nickel seals in the design, NESC elected to run a series of independent tests to ensure the seals and propellants were compatible. Aerojet was commissioned to conduct an accelerated aging test of the Voi-Shan nickel seals at elevated temperature and pressure, along with a room temperature "beaker soak test." The accelerated test will yield quick results, while the room temperature test will serve as a control to verify any positive evidence of decomposition is not due only to a temperature/pressure environment unlikely to be experienced by the spacecraft. Complete details of the Aerojet testing are included in Appendix E, and results will be provided in an addendum to this report.

9.1.3 – Post-Assembly Leak Checks

Leak checks provide confidence fluid fittings have been properly assembled and validate the overall integrity of the joints. They must be conducted at flight pressure, using media no more viscous than the propellants themselves and instrumentation suitable for detecting leaks at the smallest allowable level. Given the relatively low internal volume of the CALIPSO spacecraft and Delta-II launch vehicle fairing, hydrazine leakage at a detectible level may result in an accumulation that violates the OSHA PEL of 1 ppm during the 36-day period between propellant servicing and launch. The industry-standard approach to such situations is to conduct leak checks at flight pressure with helium using a mass spectrometer as a detector. Helium leak checks provide significant margin (approximately three orders of magnitude) over liquid hydrazine leakage. Therefore a system verified leak tight with helium ($<10^{-6}$ scc/sec) will be leak tight for hydrazine unless a sufficient upsetting event occurs to change the status of the fitting[7].

CNES has indicated helium leak checks of the Proteus bus were conducted on a fitting-by-fitting basis after initial assembly. Total system leakage will be measured with an encapsulated helium mass spec before integration of the propulsion bus and again after environmental testing of the spacecraft. Specified limit for these tests is 8.4×10^{-5} scc/sec[17]. A final 12-hour decay test will be performed at the launch site before propellant servicing. NESC was not provided any other details regarding the leak test methods, specifications (including derivation of the 8.4×10^{-5} scc/sec limit), or detection equipment to be used for these tests. Bagging and long duration mass spectrometer measurements at both high and low pressure would provide maximum confidence that fittings do not have small but growing defects that could eventually leak hydrazine[7].

NESC-R-003 – Program shall demonstrate that the Proteus bus mechanical fittings are rigorously tested using techniques adequate to validate system integrity. Leak check procedures shall specify test method, equipment to be used, media, test pressure and allowable leak rate.

While CNES indicated spacecraft environmental tests would simulate qualification-level vibration and thermal loads, NESC was not provided specific data describing the test series. If the acceptance test loads envelope shipping, transport and handling loads expected from propellant servicing through launch, the post-environment test leak check will serve not only to certify the assembly for the expected flight environment, but also as an effective screen for any fitting that may have passed initial leak checks at low (false) torque. During the site visit, VAFB relayed that the highest shock loading recorded during transport of a spacecraft was 0.6 g's. By comparison, the low frequency Delta II launch environment is 40 g's with high frequency response up to 2,500 g's[18]. Acceptance testing to these or higher levels would certainly envelope the expected ground processing loads.

NESC-R-004 – Program shall demonstrate that thermal and vibration loads applied to the spacecraft during environmental tests envelope conditions it will experience from servicing through launch.

9.1.4 – Handling Environment

Fluid fittings could be loosened if subjected to significant internal pressure or thermal transients. The period of highest vulnerability is during dynamic testing, especially propellant servicing, when pressures are cycled and the potential for flow-induced vibration exists. There is no indication that CALIPSO Proteus bus fittings will be subjected to cyclic thermal or transient pressures significant enough to cause leakage, and the induced vibration potential is minimal given the short line lengths and low flow rates involved. However, since the CALIPSO servicing procedures were not available for review, NESC was unable to assess controls placed on temperature, pressure and flow transients during hydrazine loading.

NESC-R-005 – Program shall demonstrate that servicing procedures adequately control temperature, pressure and flow rates to minimize the potential for leakage.

Even with all controls in place, the possibility of leakage still exists. Consequently, the program must take all reasonable precautions to ensure the spacecraft is monitored and personnel can be safely evacuated in the event of a leak. Industry-standard measures include a mix of fixed and portable vapor detectors capable of monitoring in the appropriate range, area-warning systems and fixed control areas limiting the number of personnel with access to the spacecraft.

A site visit to VAFB was performed on December 17, 2003, to review the two potential payload processing facilities that will be used for CALIPSO and the Delta II launch pad "white room." A map of VAFB locating the various facilities is included as Appendix D. While the Astrotech facility was toured, the Spaceport Systems International (SSI) facility was under a security lockdown and was inaccessible. Hydrazine detectors used in the Astrotech facility can resolve leaks down to 0.001 ppm and typically are calibrated and set to sense at 0.005 ppm or one half of the ACGIH TLV. The Astrotech fixed detectors are Zellweger Analytics SPM line powered units with 0.005/0.010 ppm gas calibration keys while the portable units are SPM Z purge monitors with 0.005/0.010 ppm gas calibration keys. Both audible and visual alarms are tripped at 0.005 ppm and the automated response system commands roof louvers open and air exhaust fans to maximum capacity. Portable detectors are used at the beginning of every work shift to sweep the area for leaks before personnel are allowed to enter. A drain trench completely encompasses the area where CALIPSO will be fueled and serviced, and can easily capture the 30 kilograms (approximately 8 gallons) of hydrazine in the Proteus system. Similar detection schemes with alarms are used at the pad white room[6].

The Astrotech payload processing facility fire protection system incorporates dry- and wet-pipe deluge systems designed to meet code requirements while protecting hardware from damage caused by inadvertent activation.[19] Facilities are equipped with UV and IR detectors for continuous monitoring of high-hazard areas as well as ceiling-mounted smoke/heat detectors. Hydrazine sensors have fire alarm set points at one quarter the lower explosive limit (i.e., ¼ x 4.7 or 1.175 percent hydrazine in air). These alarms communicate with the base emergency response units. If SSI is selected to process CALIPSO, the project should verify the SSI detectors and alarms meet or exceed the capabilities stated above for the Astrotech facility.

Post-servicing operations in the vicinity of the CALIPSO spacecraft will be tightly controlled. "Amber light" operations will be in effect in the payload processing facility and at the SLC-2 launch pad white room. Per memo from the Air Force 30th Space Wing[20], "A flashing amber light indicates a hazardous operation is in progress in the controlled area. Non-essential personnel shall be cleared from the controlled area. Personnel shall not enter without permission from the safety official or in the absence of the safety official the entry control authority. Only mission essential personnel will be allowed near the spacecraft, all preventive measures will be instituted, facilities will be verified acceptable to handle a maximum credible spill and emergency response will be available and on call."

In the judgment of the NESC assessment team, the mix of hydrazine vapor detectors, fire detection and suppression equipment and personnel controls are adequate for conducting safe operations in vicinity of the CALIPSO spacecraft.

NESC-R-006 – Program shall verify that the controls at the processing facility and launch pad identified above are in place to monitor for leakage from the time hydrazine is loaded until final closeout for launch. Additionally, the program shall verify that spacecraft operations are minimized after hydrazine loading, and that provisions are made for area securing and the rapid evacuation of personnel should a leak develop. Further, the program shall coordinate with all other payload/Delta II processing personnel to ensure the program's approach for minimizing personnel exposure to potential hazards is properly integrated.

9.2.0 – Thruster Leakage

Thrusters selected for the Proteus bus are designed with normally closed series-redundant solenoid-actuated flow control valves manufactured by Moog. The thrusters are of a mature design. A schematic of the valve is depicted in Figure 4.

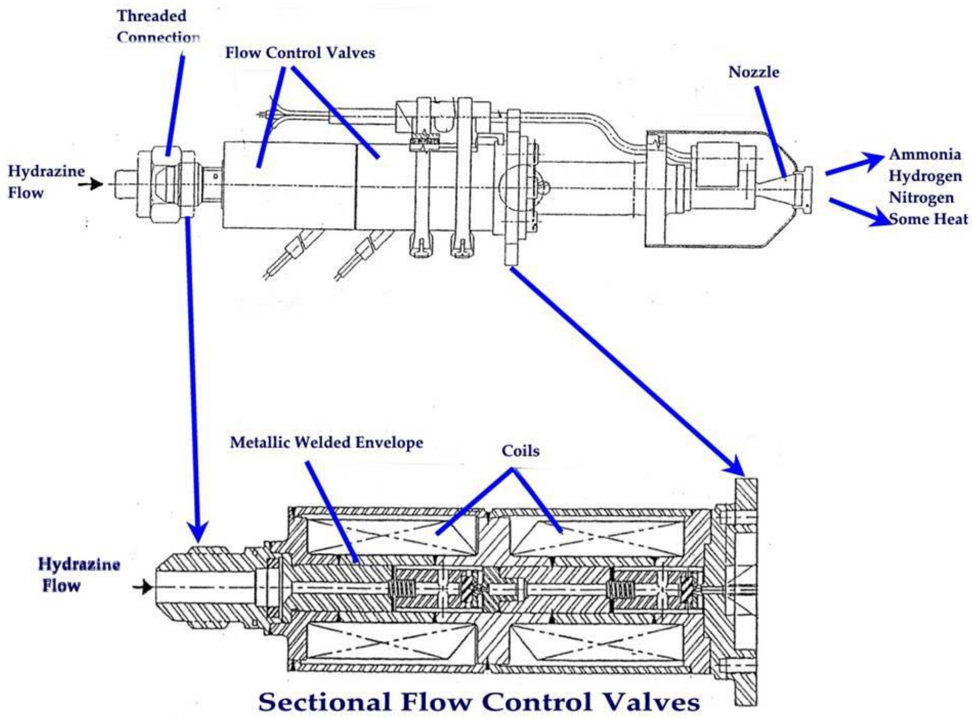

Figure 4. Moog Dual Seat Dual Servo Thruster Valve

NESC concludes the potential for external leakage from the thrusters either internally (across the control valves) or externally (thruster casing or seal) poses acceptable risk to personnel providing the program conducts an adequate pre-servicing leak check of each valve. While the program did indicate such testing was planned, NESC was not provided a specific description of the test or its pass/fail criteria.

NESC-R-007 – Program shall demonstrate that pre-servicing thruster leak checks will be adequate to validate system integrity. Leak check procedures shall test each valve independently and shall specify test method, equipment to be used, media, test pressure and allowable leak rate.

During a site visit to Aerojet Space Propulsion, an issue with Moog thruster valves similar or identical to the Proteus valves came to light. A manufacturing process change by Moog resulted in a recall investigation on suspect serial number valves[21]. The program was notified of this and was working to clear the CALIPSO Proteus bus valve set.

NESC-R-008 Program shall verify that the Proteus Moog valves on CALIPSO do not have defective plunger assemblies.

9.3.0 – Thruster Inadvertent Firing

The Proteus thruster firing circuit incorporates a number of controls to ensure valves are not inadvertently opened causing a thruster to fire. NESC concurs the controls are adequate, but recommends further steps be taken to positively preclude the possibility of an inadvertent command during periods of dynamic testing, especially power-up. A schematic of the thruster wiring circuit is shown in Figure 5. It is worth noting that the Astrium specification sheet for the thruster lists nominal flow rate at 0.44 grams per second. Even with all four (4) thrusters firing at nominal flow rate, it would take 4.7 hours to drain the 30 kilograms of hydrazine in the propellant tank.

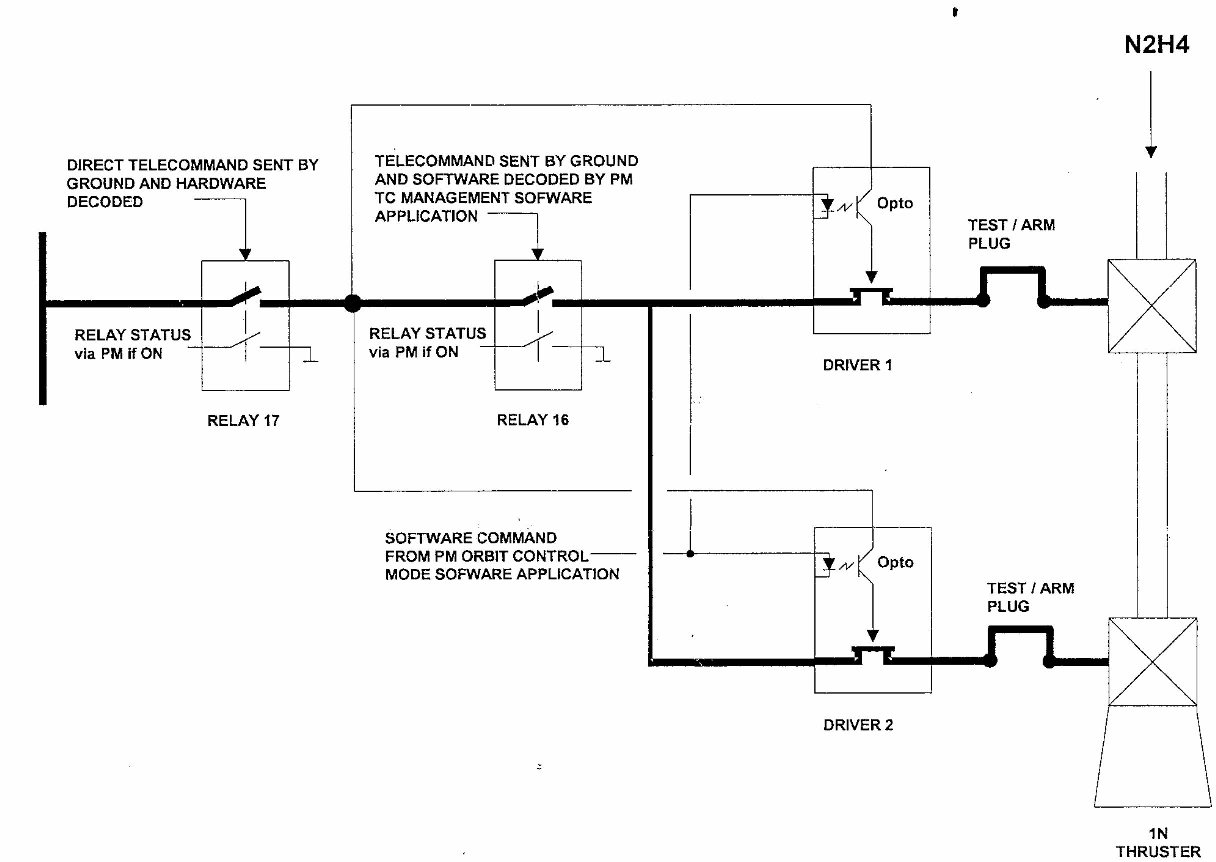

Figure 5. Thruster Circuit Schematic with New Test/Arm Plugs (PM refers to spacecraft processor module)

NESC-R-009 – Program shall demonstrate that test procedures verify relays 16 and 17 are open before power is applied to the spacecraft. Since the design incorporates latching relays, verification of the last stable state by data retrieval or written record is acceptable.

NESC-R-010 – Steps for inserting and removing test/arm plugs shall be explicitly called out in the ground processing timeline. Final installation for flight shall occur as late as possible; until that time, plugs shall only be installed as required for thruster valve testing.

NESC-R-011 – Program shall verify that all thruster firing circuit inhibits function as designed.

10 Conclusion

It should again be noted that key CNES information requested for this assessment through the GSFC program office was not provided (ref. Appendix A). This fact limited the review team's ability to draw conclusions based on objective evidence and formed the basis for many of the requirements. At this time, the NESC cannot objectively conclude that the Proteus bus as designed poses either acceptable or unacceptable risk to personnel. The program must adequately address all eleven (11) requirements stated in this report before the NESC can conclude personnel risk is acceptable. These requirements call for review of CNES assembly and acceptance test procedures and verification that the planned acceptance testing and integrity checks are performed by CNES before hydrazine is loaded into the system. Further, verification of the planned operational controls (e.g., leak detection, alarms, installation of thruster arm plugs, personnel controls and minimizing spacecraft operations once loaded) are required to mitigate the risks to an acceptable level. Compatibility of hydrazine with the Voi-Shan nickel conical seals will be determined through an ongoing series of tests being conducted by Aerojet and test results will be documented in an addendum to this report.

The expected response from the CALIPSO program to the NESC will be an action plan indicating how the program will implement the eleven (11) NESC requirements using their in-line engineering, operation and safety organizations. NESC will approve the action plan and determine the adequacy of the program's responses. As originator of the actions, NESC will provide status (open or closed) on each requirement at the appropriate CALIPSO milestone review prior to hydrazine loading. The program should use Appendix C as a guide to address the NESC's requirements.

11 Minority Report

The assessment team observed that there is no isolation valve downstream of the CALIPSO propellant tank. The GRC members were of the opinion that the program needed to address this issue in response to a specific NESC recommendation and offered the following:

> "The lack of an isolation valve in the Proteus bus design maximizes the potential for loss if any one of the three hazardous events were to occur, since there would then be no expedient means to stop the flow of hydrazine from the propellant tank. As a result, the worst-case failure effect is that most of the hydrazine in the propulsion system would be released, possibly causing a catastrophic event (personnel injury or fire). There is no evidence that a formal risk assessment was performed to address these three hazardous events related to the design decision to omit an isolation valve."
>
> ***"Minority Opinion Recommendation - Program should perform or make available a formal risk assessment to address the three hazardous events related to the design decision to omit an isolation valve. As part of including an isolation valve in the design, this assessment should consider the replacement of the mechanical fitting closest to the tank with a welded joint."***

Two NESC Review Board members concurred with including this recommendation in the final report. The remainder did not, however, so by Board consensus it was rejected. While a thorough risk assessment early in the design process might have led to a different design solution, an assessment performed today would not reduce the potential for leakage from the fittings or thrusters and thus would not help mitigate the risks associated with the current design. Instead of incorporating the suggested recommendation, the Board ensured the lessons learned from this study and documented in Section 12 highlighted sound design solutions and underscored the need for thorough risk assessments early in the planning of any project.

12 Lessons Learned

Project managers should strive to ensure issues are surfaced and resolved, through independent assessment if necessary, early in the design process so technical changes can be effected with fewer cost and schedule implications. Thorough risk assessments must be performed to arrive at a configuration that presents the overall minimum risk to personnel, the mission and the environment. Such assessments should be well documented, approved through a formal process, and made available for reference should questions arise as a project proceeds.

When NASA is involved in missions with outside partners, the level of NASA insight and influence on non-NASA hardware design, verification and acceptance testing should be documented, clearly communicated, and carried as a project risk to be tracked. There was clearly confusion over certain safety requirements among the organizations involved in CALIPSO. The roles of various in-line and independent safety organizations should be clearly defined and their expectations documented as project requirements. Projects should then act to meet these requirements or, when warranted, process waivers with rigorous, documented, technical rationale.

Properly welded fluid connections are inherently more reliable than mechanical fittings and should be incorporated in fluid propulsion designs employing hazardous commodities whenever possible. This requirement should be reflected in appropriate Agency-level design standards and variance accepted only when accompanied by appropriate risk trades and supporting technical rationale.

Since lock wire does not prevent torque relaxation, it cannot be relied upon as a secondary locking device to prevent fluid fitting leakage. NASA or industry should spearhead development of a redundantly-sealed fluid fitting with an integral locking feature that, once engaged, will positively preclude loss of clamping force at the sealing surfaces. Ramped, inter-locking teeth between the inside rear of the B-nut and back of the tube end might serve this purpose if the ramp angle and teeth were sized to prevent nut rotation and loss of axial load with the fitting at full torque (ref Nord-Lock Bolt Securing System, Nord-Lock AB, Mattmar, Sweden, www.nord-lock.com.)

References

(1) NASA Procedural Requirement NPR-8715.3, “NASA Safety Manual”, Change 1, June 19, 2003.

(2) CALIPSO-Tailored Eastern and Western Range 127-1 Safety Regulations, Doc. TP2.LB.0.AQ.1836 ASC dated October 21-22, 2002.

(3) National Institute for Occupational Safety and Health (NIOSH), “Pocket Guide to Chemical Hazards”. U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention. Cincinnati, OH. 1997.

(4) Occupational Safety and Health Administration (OSHA), "Occupational Safety and Health Standards, Toxic and Hazardous Substances". *Code of Federal Regulations*. 29 CFR 1910.1000. 1998.

(5) American Conference of Governmental Industrial Hygienists (ACGIH), "1999 TLVs and BEIs. Threshold Limit Values for Chemical Substances and Physical Agents, Biological Exposure Indices". Cincinnati, OH. 1999.

(6) Email from Thomas Palo, KSC Launch Services Program Safety and Mission Assurance Office, dated 1-9-04 with attachment - "CALIPSO Propulsion System Safety Assessment", dated December 2003.

(7) K. Coste, "Summary Comments on NESC CALIPSO Review", Aerospace Corporation TOR#2004(2181)-1, January 9, 2004.

(8) John H. Bickford, "An Introduction to the Design and Behavior of Bolted Joints", Third Edition, p. 553. Marcel Dekker, Inc. 270 Madison Avenue, New York, NY, 10016. 1995.

(9) Results of Evaluation Tests Conducted on Voi-Shan Conical Seals, Voi-Shan Engineering Report No. 249-64, March 6, 1964.

(10) EURECA – 31654-RP-EA-103, ISS.1, "Qualification Test Report for the ENN 51200-Size 4 European Retrievable Carrier", June 28, 1989.

(11) S. Georgian et al, "Experiments on the Robustness of Separable Fittings", AIAA#96-3116, 32nd Joint Propulsion Conference, July 1-3, 1996, Lake Buena Vista, FL.

(12) MSFC –HDBK-527, rev. F, "Material Selection List for Space Hardware Systems," September 30, 1988.

(13) B. Quill, "Spill Prevention Guidance Document", Appendix E – Chemical Compatibility Matrix, Users Guide UG-2033-ENV, Naval Facilities Engineering Research Center, October 1998.

(14) E. Cadwallader and L. Piper, "Hydrazine Compatibility Survey", CPIA Publication 236, June 1973.

(15) L. Toth et al, "Propellant/Material Compatibility Program and Results", NASA Technical Memorandum 33-779, August 15, 1976.

(16) M.D. Pedley et al, “Explosion, Compatibility and Safety Hazards of Hydrazine”. RD-WSTF-002, NASA Johnson Space Center White Sands Test Facility, February 20, 1990.

(17) NESC–CALIPSO Propulsion Brief-6 by Don Porter, LaRC Mission Assurance Office, “Design for Minimum Risk Information”, p. DJP-23, November 5, 2003.

(18) Boeing Delta II Interface Control Document for CALIPSO, MCD 01H0074 New, March 31, 2003.

(19) Astrotech VAFB Facility Safety Manual, SHI-ASO-M0011, Revision B, February 7, 2002.

(20) Memo dated November 17, 2003, from Air Force 30th Space Wing Chief of System Safety, Micheal McCombs.

(21) Lockheed Martin Space Systems Mission Success Bulletin #03-32, “Moog Dual Seat Propellant Valve with a Defective Plunger Assembly”, December 12, 2003.

List of Acronyms

ACGIH TLV	American Conference of Governmental and Industrial Hygienists' threshold limit value
A/N	Army/Navy
CALIPSO	Cloud-Aerosol LIDAR and Infrared Pathfinder Satellite
Observations	
CNES	Centre National d'Etudes Spatiales
EURECA	European Retrievable Carrier
EWR	Eastern and Western Range
GRC	Glenn Research Center
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
ITA/I	Independent Technical Assessment/Inspection
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LIDAR	Light detecting and ranging
N_2H_4	Anhydrous Hydrazine
NCE	NESC Chief Engineer
NESC	NASA Engineering and Safety Center
NIOSH IDLH	National Institute of Occupational Safety and Health immediately dangerous to life or health limit
OSHA PEL	Occupational Safety and Health Administration permissible exposure limit
PM	Processor Module
ppm	parts per million
psig	pounds per square inch gage
scc/sec	Standard cubic centimeters per second
SLC	Space Launch Complex
SSI	Spaceport Systems International
VAFB	Vandenberg Air Force Base
WSTF	White Sands Test Facility

Approval and Document Revision History

Approved:	Original signature on file	5-7-04
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
0.01	CALIPSO Independent Technical Assessment/Inspection (ITA/I) Report	Richard J. Gilbrech	1-27-04

NESC Independent Technical Assessment Team

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Approved: Original signature on file — 1-27-04
Ralph R. Roe — Date
NESC Director
NASA Langley Research Center

Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

Final Update 1-20-04

No	ECD	Description	Status / Comments		Actionee
1	CLOSED	Provide a briefing summarizing project background and issues	3-Nov-03	· Action assigned	Calipso Project
			6-Nov-03	· Complete	
2	CLOSED	Provide a briefing summarizing safety issues with Calipso design	12-Nov-03	· Action assigned	Goddard Safety
			13-Nov-03	· Complete	
3	CLOSED	Provide detailed mechanical fitting configuration data including part numbers, materials, torque specifications	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Should be able to answer this with information available in various documents, visits to Alcatel, etc. Data to be provided by Nov 28.	
			25-Nov-03	MSPSP contains some data	
			1-Dec-03	CNES provided more details	
			15-Dec-03	CNES provided material and wall thickness of tubing	
4	CLOSED in part	Provide mechanical fitting qualification and acceptance test data.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· SOHO qual test data is identical to that used for Calipso. SOHO data provided. Need Calipso acceptance test data.	
5	CLOSED in part	Provide detailed mechanical fitting installation procedure including alignment verification, thread lubrication, and torque.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Jim Free provided some details	
			1-Dec-03	CNES provided some details but no procedures for review	
			22-Dec-03	Requested grease application (how much and were) on 12-4-03 - no response provided	

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No	ECD	Description	Status / Comments		Actionee
6	CLOSED in part	Provide detailed fluid system configuration drawing showing component locations (tank, lines, fittings, brackets, thrusters), line routing, and line lengths	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Alcatel will not provide this detail	
			16-Dec-03	CNES provided one drawing with thruster locations - no tubing or clamp layout dimensions.	
7	CLOSED in part	Provide detailed summary of mechanical fitting leak check procedures, specifications, and test results	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Jim Free email provided some detail	
			1-Dec-03	CNES provided some details	
			15-Dec-03	CNES provided detailed summary of procedures, no pass/fail criteria or test results from subassembly checks to date.	
8	CLOSED	Provide summary of environments to which propulsion system will be exposed following hyper servicing, to include vibration, pressure, and thermal.	6-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Once fueled, the only environmental change is vibration from the move to the pad. Process timeline to be provided by Nov 28.	
			25-Nov-03	Jim Free provided schedule with limited details and information on processing facility environment	
			17-Dec-03	Julie Schneringer (KSC resident office at VAFB) provided shock information on transporter for previous missions and detailed ground processing timeline for Jason 1.	

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Calipso Project Assessment Actions

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No	ECD	Description	Status / Comments	Actionee
9	CLOSED	Provide mass properties of key propulsion system components, esp. tank, lines, and thrusters.	6-Nov-03 · Action assigned - due Nov 24 24-Nov-03 · Data requested of CNES Nov 24. 25-Nov-03 MSPSP provides some details 5-Dec-03 Don Porter provided thruster mass and dimensions 16-Dec-03 CNES provided estimated mass of tank, lines and thrusters	Calipso Project
10	1-Dec-03	Determine whether mechanical fitting qual tests are adequate to address expected environment.	6-Nov-03 · Action assigned - due Dec 1 22-Dec-03 Waiting on CNES data package	NESC Team
11	CLOSED	Identify additional testing required to assess suitability of mechanical fittings for use on Calipso spacecraft.	6-Nov-03 · Action assigned - due Dec 1 17-Dec-03 Insufficient configuration data to make vibe/leak tests traceable to flight	NESC Team
12	24-Nov-03	Provide thruster qualification and acceptance test data.	6-Nov-03 · Action assigned - due Nov 24 24-Nov-03 · Data requested of CNES Nov 24. Data presently available to be provided by Nov 28. 15-Dec-03 CNES assembling data package for mail delivery	Calipso Project
13	1-Dec-03	Determine whether thruster qual tests are adequate to address expected environment.	6-Nov-03 · Action assigned - due Dec 1 22-Dec-03 Waiting on CNES data package	NESC Team
14	1-Dec-03	Identify additional testing required to assess suitability of thrusters for use on Calipso spacecraft.	6-Nov-03 · Action assigned - due Dec 1 17-Dec-03 Insufficient configuration data to make vibe/leak tests traceable to flight. Availability of Astrium thruster and facility to test not achievable in short term. Awaiting CNES data package.	NESC Team

Appendix A. NESC CALIPSO Assessment Action Item List

Calipso Project Assessment Actions

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No	ECD	Description	Status / Comments		Actionee
15	CANCELLED	Review Calipso propulsion system with respect to EWR 127-1 requirements.	6-Nov-03	· Action assigned - Due Dec 5	Aerojet
			22-Dec-03	Non-Disclosure Agreement delays - cancelled action	
16	CLOSED	Provide a copy of the tailored EWR 127-1 requirements	13-Nov-03	· Action assigned	Goddard Safety
			17-Nov-03	· Closed. Data provided.	
17	CLOSED	Provide contacts at SSI and Astrotech	13-Nov-03	· Action assigned	Goddard Safety
			17-Nov-03	· Closed. Contact info provided.	
18	CLOSED	Provide questions for Alcatel site visit.	13-Nov-03	· Action assigned	NESC Team
			14-Nov-03	· Closed. Questions forwarded to Calipso Project.	
19	CLOSED in part	Provide electrical drawings detailing operation of test and arm plugs.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			25-Nov-03	Drawing provided w/o operations details	
			22-Dec-03	Julie Schneringer (KSC resident office at VAFB) provided detailed ground processing timeline for Jason 1. Still need point where arm plugs are installed (added after Jason)	
20	CLOSED	Provide a copy of the Jason-1 servicing (ML 902, 908, 920, 934 & 950) and emergency offload (ML 925 & 926) procedures. Note: Calipso procedures available no earlier than 6 months before launch (June 2004).	14-Nov-03	· Action assigned - due Nov 24	Calipso Project
			24-Nov-03	· Data requested of CNES Nov 24.	
			1-Dec-03	Servicing procedure supplied, emergency offload procedure deferred to Boeing	
			15-Dec-03	CNES provided ML 925 and ML 926 procedures. Requested ML 902, 908, 920, 934 & 950 from VAFB	
			26-Dec-03	Received remainder of procedures from Ed Henry of VAFB	

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Calipso Project Assessment Actions

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No	ECD	Description	Status / Comments		Actionee
21	CLOSED	Provide a copy of the Project MSPSP.	14-Nov-03 24-Nov-03 25-Nov-03	· Action assigned - due Nov 24 · Copy available in LiveLink at LaRC. Passwords to be provided by Nov 28. Jim Free provided electronic copy	Calipso Project
22	CLOSED	Provide a ground operations timeline detailing tasks performed and personnel access from spacecraft servicing through launch.	14-Nov-03 24-Nov-03 25-Nov-03 17-Dec-03	· Action assigned - due Nov 24 · Data to be provided by Nov 28. Jim Free provided schedule with limited details Julie Schneringer (KSC resident office at VAFB) provided detailed ground processing timeline for Jason 1.	Calipso Project
23	CLOSED	Provide data indicating how spacecraft is accessed for propellant servicing.	14-Nov-03 24-Nov-03 25-Nov-03	· Action assigned - due Nov 24 · Data to be provided in coordination with KSC. Available data to be provided by Nov 28. Jim Free email with pictures and details	Calipso Project
24	CLOSED	Provide data, including photographs if available, detailing accessibility of mechanical fittings and thrusters after installation in the spacecraft.	14-Nov-03 24-Nov-03 25-Nov-03	· Action assigned - due Nov 24 · Available photos will be provided by Nov 28. New pictures taken during Alcatel site visit in November will also be provided. Photos provided by Jim Free	Calipso Project
25	24-Nov-03	Provide safe life, stress, and fracture mechanics data for propellant tank. In particular, since the tank presumably captures the elastomeric bladder in a hemispherical weld joint, the fracture mechanics analysis must include an assessment of the residual stresses at this location.	14-Nov-03	· Action assigned - due Nov 24	Calipso Project

Calipso Project Assessment Actions

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No	ECD	Description	Status / Comments		Actionee
26	CLOSED	Prepare an interim summary of NESC assessment for presentation to Calipso Project.	17-Nov-03	· Action assigned - due Dec 8	NESC Team
			5-Dec-03	Provided status briefing to GSFC Deputy Center Director	
27	CLOSED	Prepare fault trees for use as assessment tools: fitting leak, thruster leak, thruster inadvertent firing.	19-Nov-03	· Action assigned - due Nov 28	Robinson - GRC
			24-Nov-03	· Preliminary fault trees have been prepared and will be forwarded for comment.	
			25-Nov-03	Preliminary fault trees forwarded for comment.	
			18-Dec-03	Updated drafts of fault trees and mitigation provided	
			22-Dec-03	Draft hazard analysis provided for comment	
			23-Dec-03	Final fault tree, mitigation and report text provided	
28	CLOSED	Determine how quickly Aerojet could set up a vibration test.	21-Nov-03	· Action assigned - due Nov 25	Aerojet
			25-Nov-03	· Vibration lab has some openings, and testing could be performed in the month of December. Need specific requirements before schedule can be finalized.	
29	CLOSED	Provide a ROM cost for compatibility and vibration tests.	21-Nov-03	· Action assigned - due Nov 25	Aerojet
			25-Nov-03	ROM Cost Delivered	

Appendix B. CALIPSO Fault Tree Analysis

Final Fault Trees for Independent Assessment of CALIPSO
By: Ed Zampino and Bill Schoren at NASA Glenn Research Center
January 8, 2004.

Three Fault Trees were developed for the Independent Assessment of CALIPSO.
The three Undesired Top Level Events were:

1. Leakage of Mechanical Fittings
2. Inadvertent opening of thruster valves L-36 days to Launch
3. Leakage of Thruster Control Valve

<u>References</u>

Presentation Slides from NESC Briefing dated November 5, 2003.
Presentation Titled: "Inadvertent Actuation of Valves," Slides NESC-CALIPSO PROPULSION, DJP-7 and DJP-9. Also, "Design Sketches & Satellite Exploded Views," Slides NESC-CALIPSO PROPULSION, DJP-2 and DJP-3.
PIC-LB-O-AN-0060-ASPI, Issue 01, from ALCATEL SPACE, Chapter 6.1.1 – Page 3, 4, and 5.
PIC-LB-O-AN-0060-ASPI, Issue 01, from ALCATEL SPACE, Page 43.
SOHO PROJECT, - JCWG #4 – PROPULSION SYSTEM ISSUES, SCREW JOINT QUALIFICATION STATUS-REPORTS- GSE SPECIFICATIONS.
Memorandum 92323ESTO392, R. Brandt. 1992.
AIAA 96-3116, "Experiments on the Robustness of Separable Fittings" S. M. Georgian et al, July 1996.
Report- "REQUESTED INFORMATION REGARDING THE PROTEUS BUS PROPULSION SYSTEM," December 2003.
CALIPSO MS Fitting Leak Test Summary Report, Prepared by D. Asato, Propulsion Branch 597, NASA Goddard Space Flight Center
Moog Space Products Division Monopropellant Thruster Valve Specification Sheet for Model 51-184.

This analysis is based on the following assumptions:

1. <u>Leakage of Mechanical Fittings</u>

a. The fittings will not go through coupling/uncoupling/re-coupling cycles during the ground test and pre-launch checkout phases. This type of wear will not be significant.
b. The coupling of the fittings, <u>if done improperly</u>, can cause damage that may lead to leaks.
c. If the couplings possess <u>structural defects</u> such cracks, major internal flaws, or they are produced out of a material that was not specified in the design, this may result in external leakage.
d. <u>Excessive Temperature</u> from some source may cause the fittings to expand and be under strain. This could cause fittings to crack (or fail) allowing leakage of N2H4. Although this condition is highly unlikely it has been included in the fault tree.

e. The fittings have to be designed to take the stress (forces) exerted from within by internal fuel line pressure (pressure of the N2H4).
f. The fittings must be designed to withstand forces from launch vibration. There are other events that can expose the fittings to shock such as equipment collision.

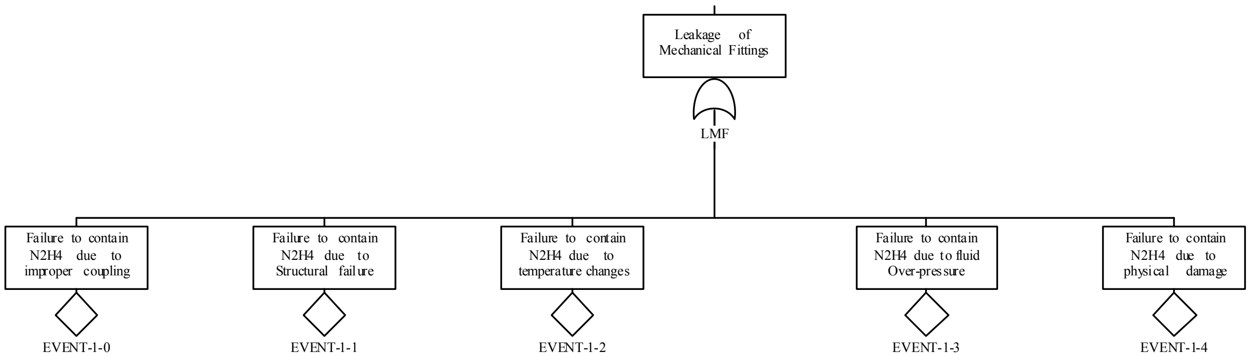
2. Inadvertent opening of thruster valves L-36 days

a. During ground testing, input power to the enabling circuits will be provided by Ground Support Equipment (GSE). During the ground testing/processing, GSE will provide power only when it is necessary to check out required system functions. Otherwise, power will not be provided.
b. The only way that power can be provided to the spacecraft (and the thruster actuation circuits) is through input ports that only connect to the GSE.
c. When input voltage is provided to the actuation circuit, a signal (tele-command) is sent to the first relay that energizes the relay.
d. When a second tele-command is sent to the second relay, the relay is energized.
e. A software command from the Processor Module (PM) orbit control mode software application is required to provide power to the Drivers 1 and 2. This action enables power to reach the solenoid valve coils in both thruster valves. (Ref. Slide DJP-4)
f. When the Arm plugs are removed from the circuit leading to the thruster valve solenoid coils, this action cuts off the physical path (breaks the circuit) by which power can be provided to the solenoid coils.
g. Even if the top (first) thruster valve coils are energized and the valve opens, this does not constitute an inadvertent firing of the 1N Thruster. Both valves must open for a thruster firing to occur.

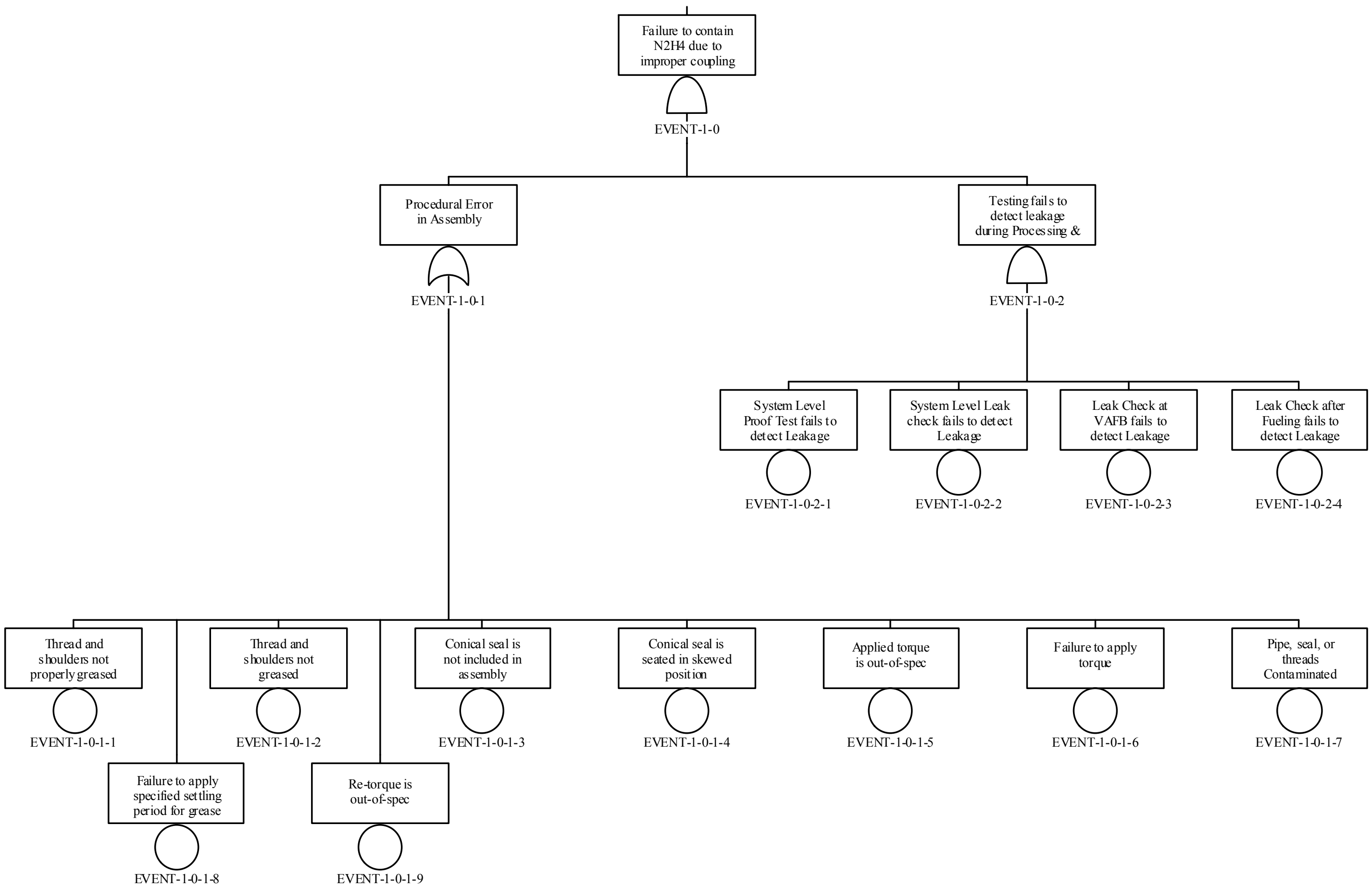
3. Leakage of Thruster Flow valve.

a. The thruster valves are not disassembled following their initial fabrication, QC Testing, and shipping from Moog Corporation. However, the assembly and testing of the thruster valves, if done improperly, can result in an undetected defective seal leading to external leaks.
b. There is a leak test performed by the valve manufacturer (Moog) and a leak check performed at the thruster level of system assembly in Germany. If these leak checks are not performed correctly and are ineffective, a defective valve could go undetected and be included as a part of CALIPSO.
c. If the welds, seams, metallic envelope, and outer casing possess structural defects such cracks, major internal flaws, or they are produced out of a material that was not specified in the design, this may result in failure: external leakage failure mode. Defective valve assembly could also lead to internal leakage. Failure of the valve to close properly (the armature/poppet assembly does not close against the valve seat) could be caused by a defective valve spring, contamination lodged between the poppet and seat, or a defective valve seat.
d. Excessive Temperature from some source may cause the seams or joints in the valve to expand and be under strain. This could cause parts to crack (or fail) allowing leakage of N2H4. Although this condition is highly unlikely it has been included in the fault tree.
e. The thruster valves have to be designed to take the stress (forces) exerted from within by internal fuel line pressure (pressure of the N2H4).
f. The thruster valves must be designed to withstand forces from launch vibration. There are other events that can expose the valves to shock such as equipment collision.

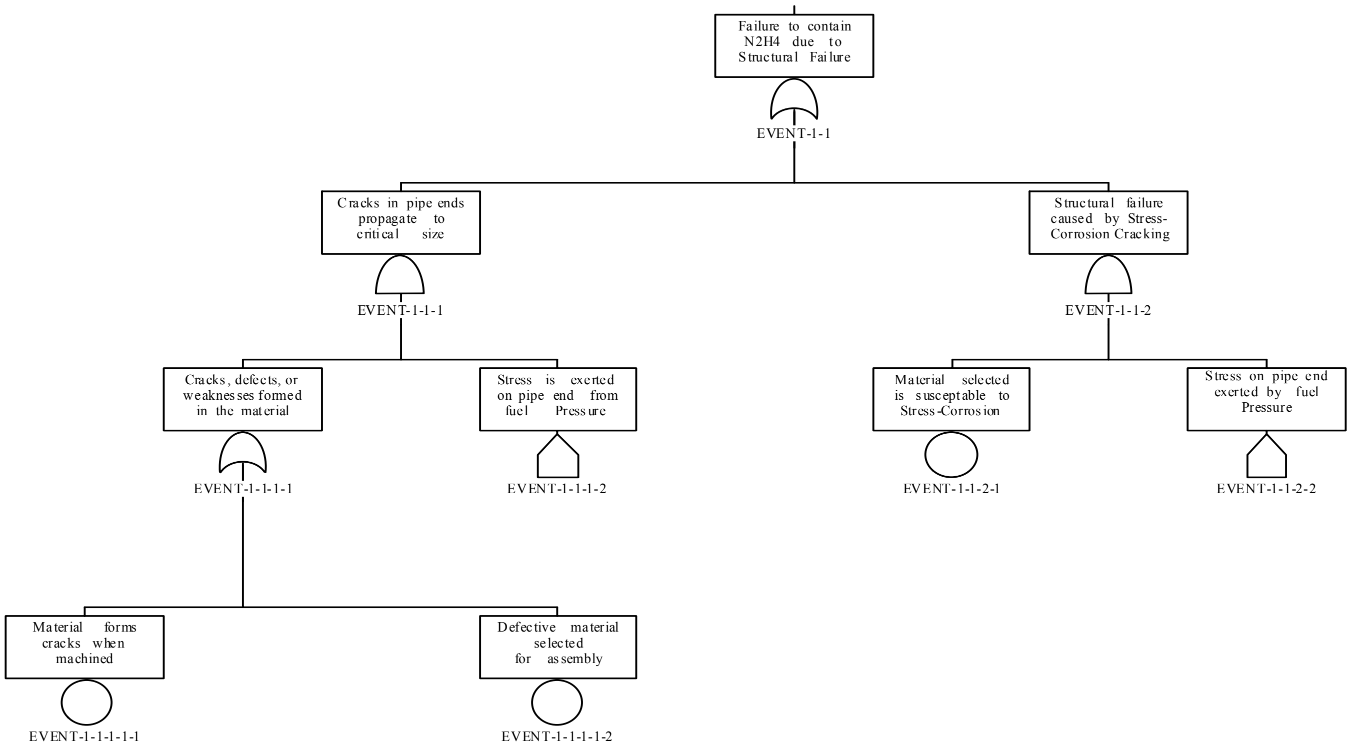
Appendix B. CALIPSO Fault Tree Analysis

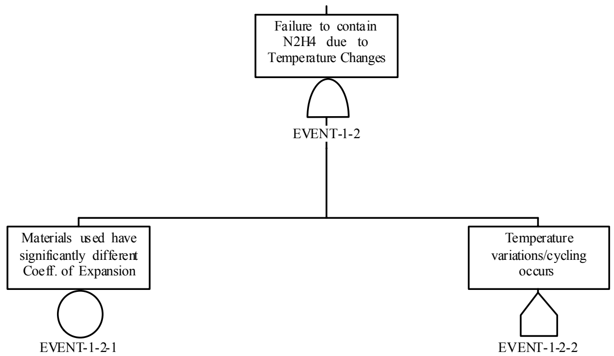


Appendix B. CALIPSO Fault Tree Analysis

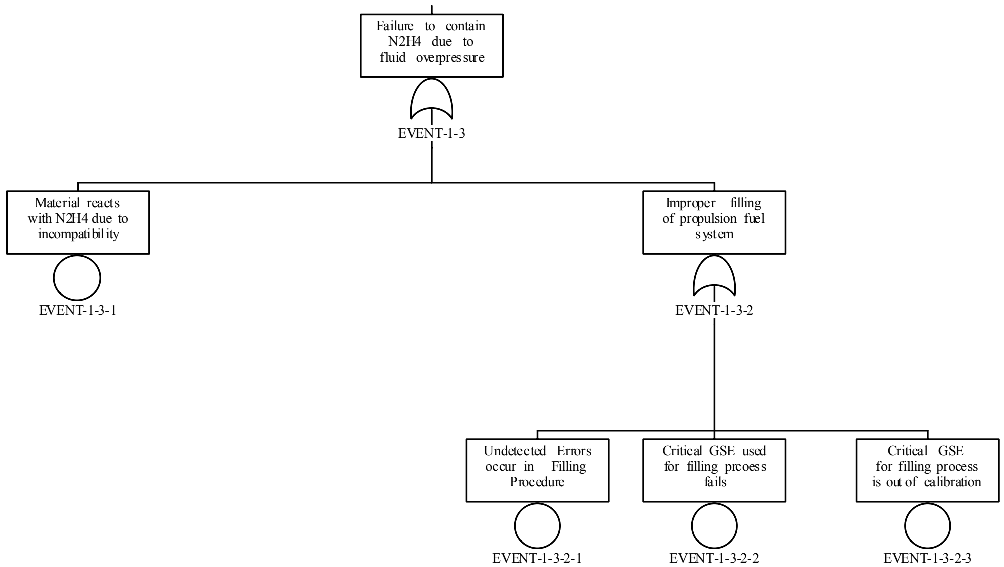


Appendix B. CALIPSO Fault Tree Analysis

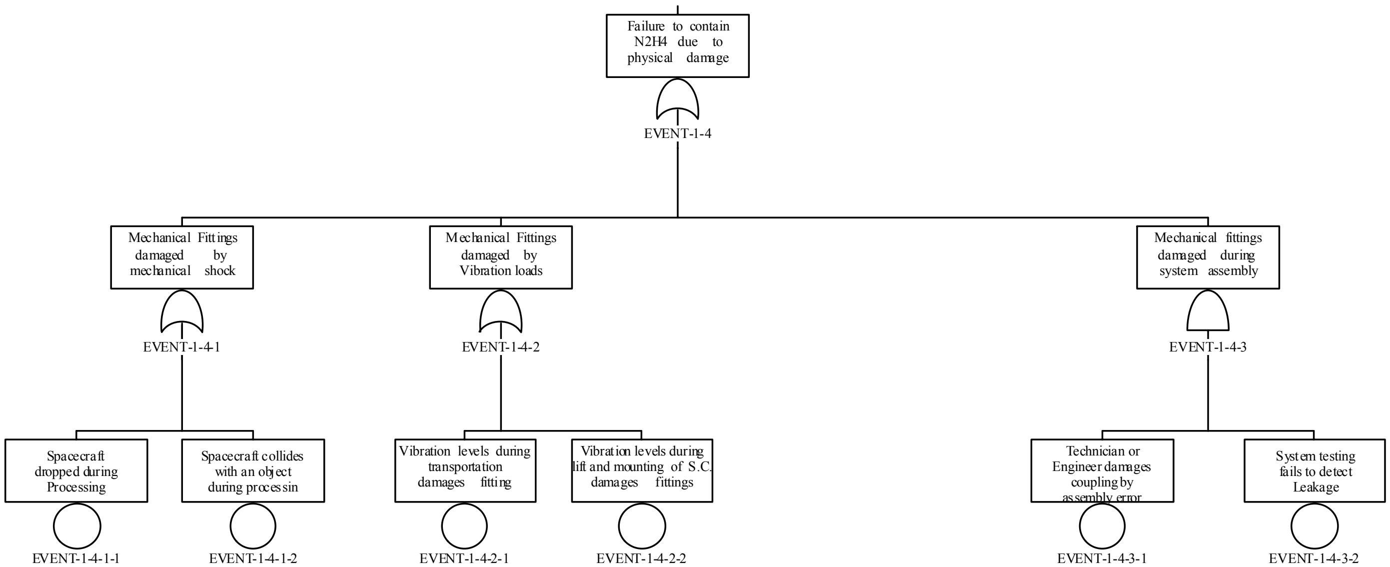



Failure to contain N2H4 due to Temperature Changes
EVENT-1-2
Materials used have significantly different Coeff. of Expansion
EVENT-1-2-1
Temperature variations/cycling occurs
EVENT-1-2-2

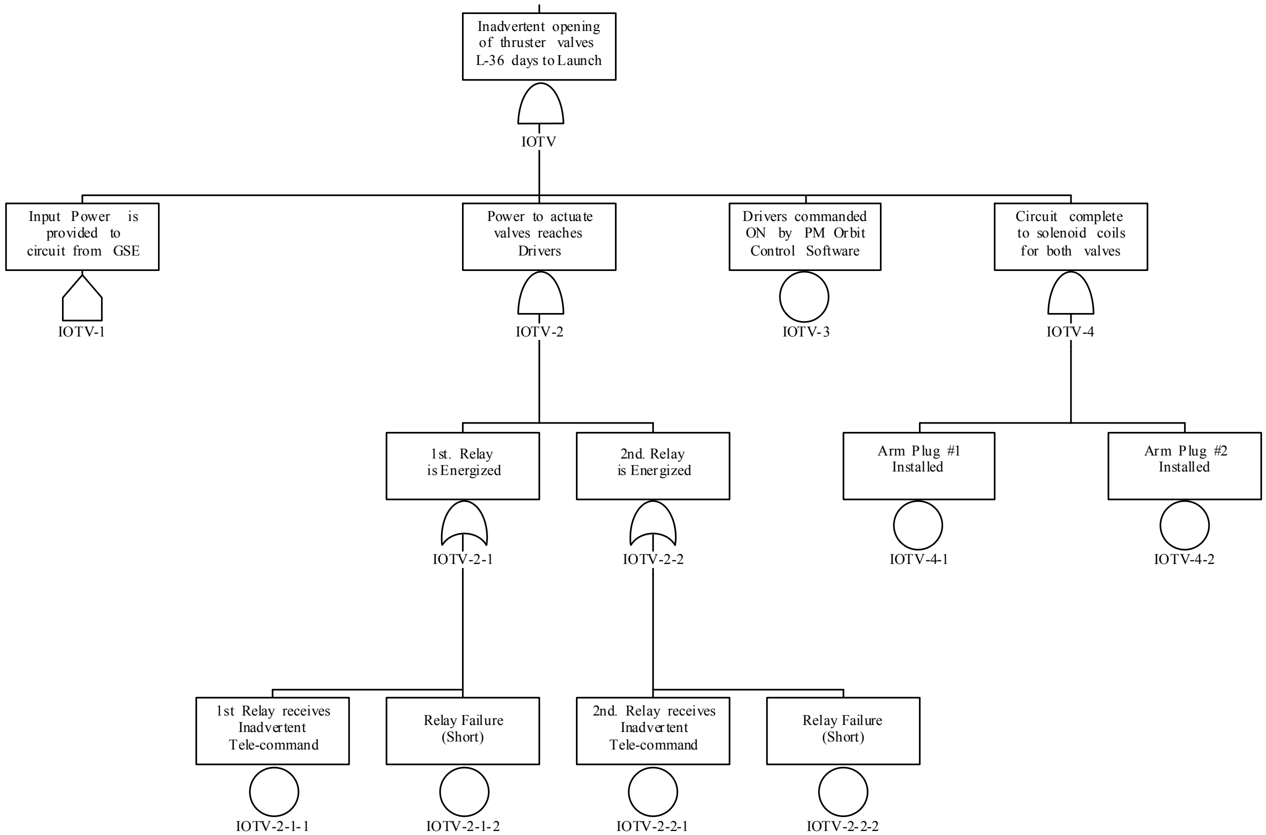
Appendix B. CALIPSO Fault Tree Analysis



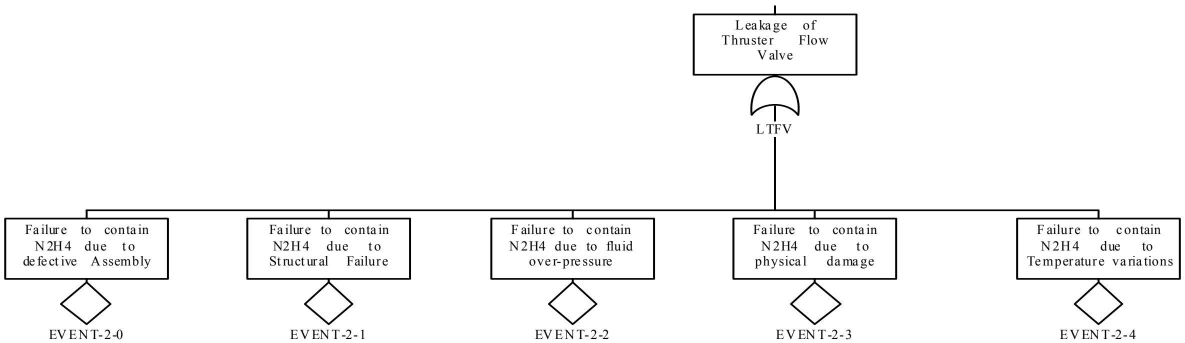
Appendix B. CALIPSO Fault Tree Analysis



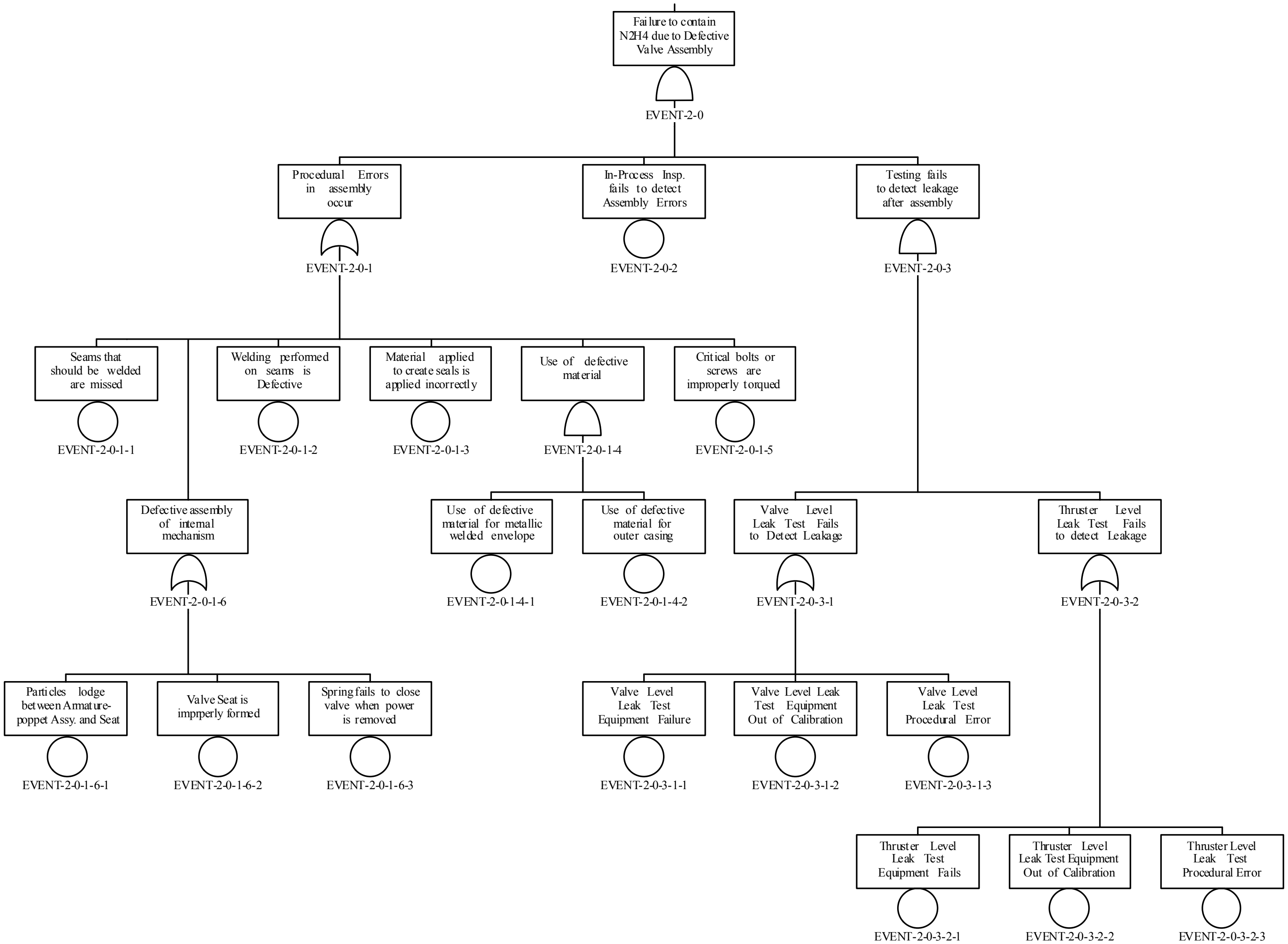
Appendix B. CALIPSO Fault Tree Analysis



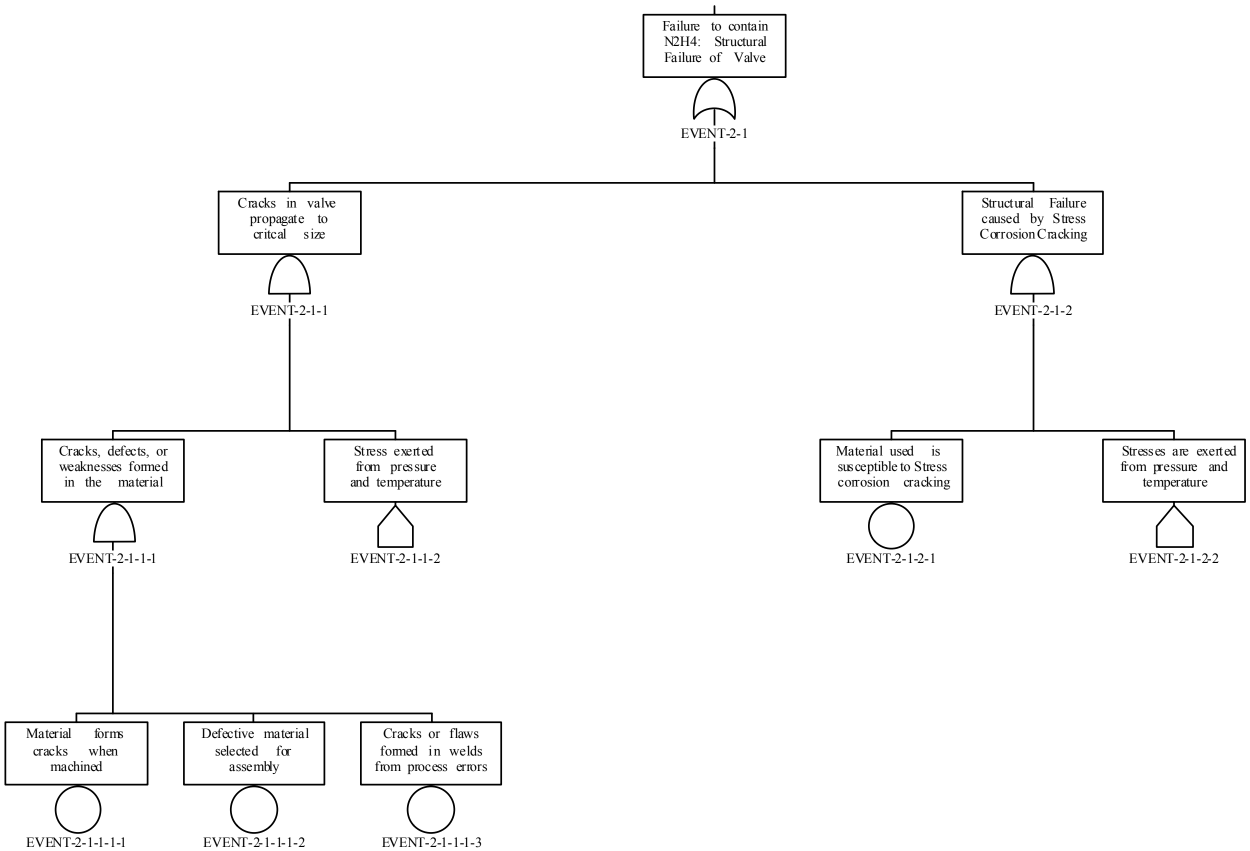
Appendix B. CALIPSO Fault Tree Analysis



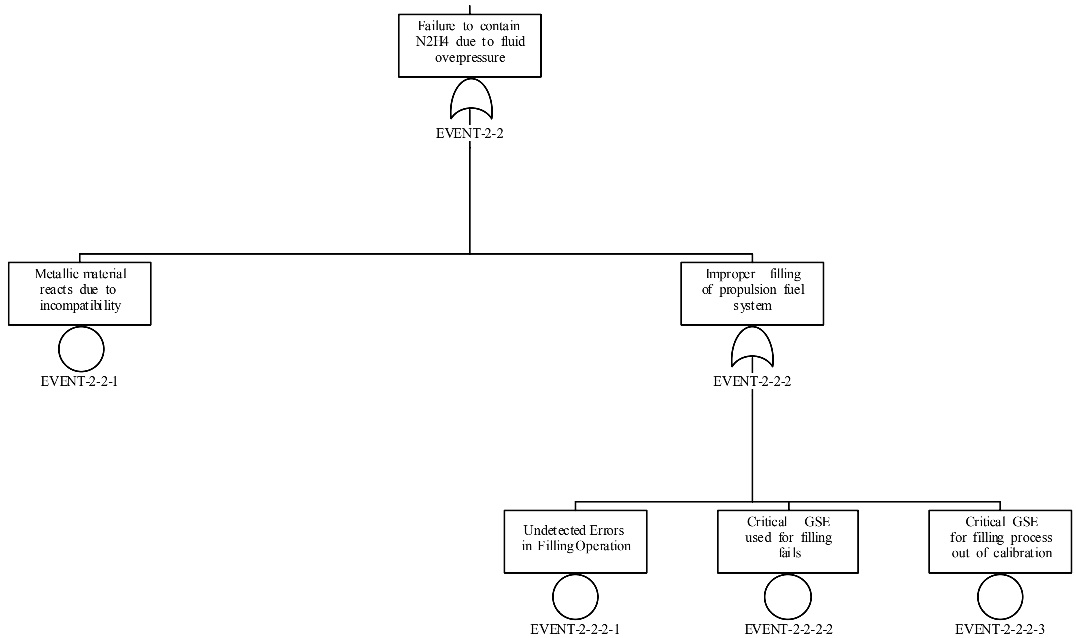
Appendix B. CALIPSO Fault Tree Analysis



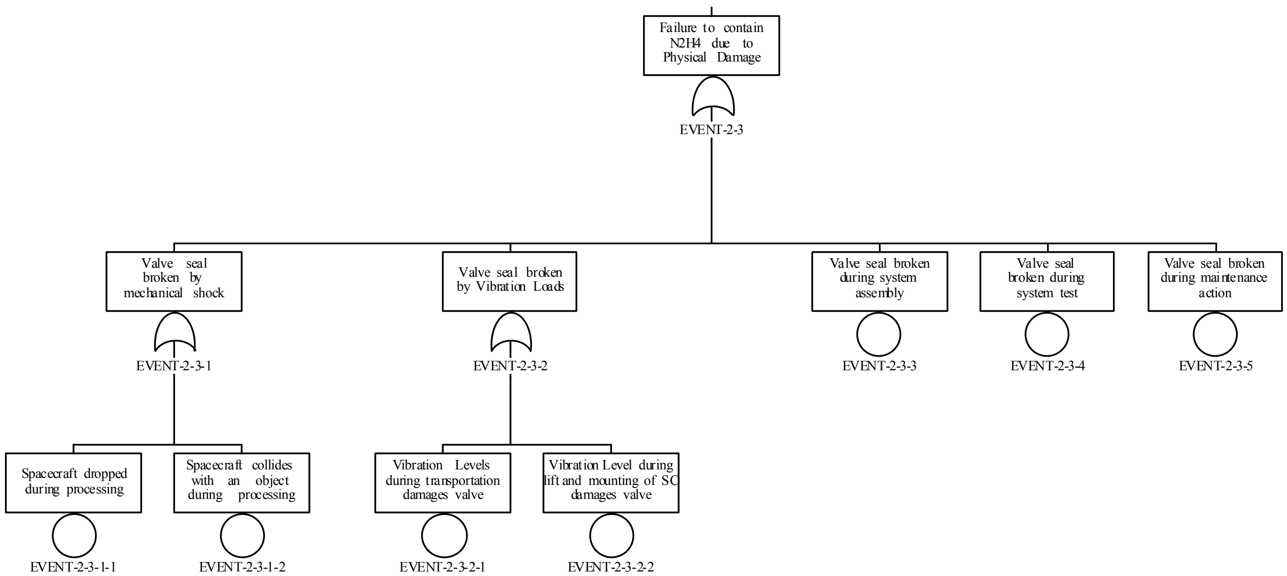
Appendix B. CALIPSO Fault Tree Analysis



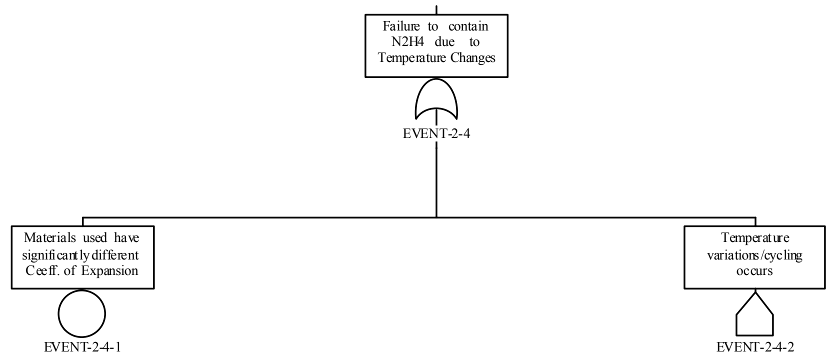
Appendix B. CALIPSO Fault Tree Analysis



Appendix B. CALIPSO Fault Tree Analysis



Appendix B. CALIPSO Fault Tree Analysis



Appendix C – CALIPSO Fault Tree Mitigation Matrix
Leakage of Mechanical Fittings

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
1-0	**Failure to contain N2H4 due to improper coupling**		
1-0-1	**Procedural Error in Assembly**		Refer to NESC-R-001 and NESC-R-002.
1-0-1-1	Thread and shoulders not proper greased		
1-0-1-2	Thread and shoulders not greased		
1-0-1-3	Conical seal is not included in assembly		
1-0-1-4	Conical seal is seated in skewed position		
1-0-1-5	Applied torque is out-of-spec		
1-0-1-6	Failure to apply torque		
1-0-1-7	Pipe, seal, or threads contaminated		
1-0-1-8	Failure to apply specified settling period for grease		
1-0-1-9	Re-torque is out-of-spec		
1-0-2	**Testing fails to detect leakage during processing & integration**		Refer to NESC-R-003.
1-0-2-1	System Level Proof Test fails to detect leakage		
1-0-2-2	System Level Leak Test fails to detect leakage		
1-0-2-3	Leak Check at VAFB fails to detect leakage		
1-0-2-4	Leak Check after fueling fails to detect leakage		
1-1	**Failure to contain N2H4 due to Structural Failure**		
1-1-1	**Cracks in pipe ends propagate to critical size**		Refer to NESC-R-002 and NESC-R-003.
1-1-1-1	Cracks, defects, or weaknesses formed in the material		
1-1-1-1-1	Material forms cracks when machined		
1-1-1-1-2	Defective material selected for assembly		
1-1-1-2	**Stress is exerted on pipe end from fuel pressure***		
1-1-2	**Structural failure caused by stress-corrosion cracking**	Analysis	Materials assessment performed to preclude use of stress corrosion susceptible materials. Closed - Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1.

* - Expected conditions

Appendix C – CALIPSO Fault Tree Mitigation Matrix
Leakage of Mechanical Fittings

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
1-1-2-1	Material selected is susceptible to Stress-Corrosion		
1-1-2-2	**Stress is exerted on pipe end from fuel pressure***		
1-2	**Failure to contain N2H4 due to Temperature Changes**	Analysis/ Inspection	Spacecraft temperature controlled to small variations during ground processing. Closed - Reference Launch Vehicle ICD MDC-01H0074.
1-2-1	Materials used have significantly different Coefficient of thermal Expansion		
1-2-2	Temperature variations/cycling occurs*		
1-3	**Failure to contain N2H4 due to Fluid Over-pressure**		
1-3-1	Material reacts with N2H4 due to incompatibility	Analysis	Material assessment performed to preclude use of materials incompatible with N2H4. Closed pending results of Aerojet compatibility tests. Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1. Materials used are compatible with N2H4 according to MSFC-HDBK-527 rev. F.
1-3-2	**Improper filling of propulsion fuel system**		Refer to NESC-R-005.
1-3-2-1	Undetected Errors occur in Filling Procedure		
1-3-2-2	Critical GSE used for filling process fails		
1-3-2-3	Critical GSE for filling process is out of calibration		
1-4	**Failure to contain N2H4 due to physical damage**		
1-4-1	**Mechanical Fittings damaged by mechanical shock**		Refer to NESC-R-004.
1-4-1-1	Spacecraft dropped during processing		
1-4-1-2	Spacecraft collides with an object during processing		
1-4-2	**Mechanical Fittings damaged by vibration loads**		Refer to NESC-R-004.
1-4-2-1	Vibration levels during transportation damages fittings		

* - Expected conditions

Appendix C – CALIPSO Fault Tree Mitigation Matrix
Leakage of Mechanical Fittings

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
1-4-2-2	Vibration levels during lifting and mounting of Spacecraft damages fittings		
1-4-3	**Mechanical Fittings damaged during system assembly**		Refer to NESC-R-001, NESC-R-002, and NESC-R-003.
1-4-3-1	Technician or Engineer damages coupling by assembly error		
1-4-3-2	System testing fails to detect Leakage		

* - Expected conditions

Appendix C – CALIPSO Fault Tree Mitigation Matrix
Inadvertent Opening of Thruster Valves

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
IOTV-1	**Input power is provided to circuit from GSE***		
IOTV-2	**Power to actuate valves reaches drivers**		
IOTV-2-1	1st relay is Energized		Refer to NESC-009.
IOTV-2-1-1	1st Relay receives Inadvertent Tele-command		
IOTV-2-1-2	Relay Failure (Short)		
IOTV-2-2	2nd relay is Energized		Refer to NESC-009.
IOTV-2-2-1	2nd Relay receives Inadvertent Tele-command		
IOTV-2-2-2	Relay Failure (Short)		
IOTV-2-3	Opt-couplers commanded ON by PM orbit Control Software		Refer to NESC-009.
IOTV-3	**Power provided to solenoid coils for both valves**		
IOTV-3-1	Arm Plug #1 Installed too early before fairing installation		Refer to NESC-R-010.
IOTV-3-2	Arm Plug #2 Installed too early before fairing installation		Refer to NESC-R-010.

Note - After propulsion system filling operations (including Launch Pad operations), inadvertent opening of a pair of thruster valves requires three commands. (Three inhibits) These commands are needed to enable the power to reach the solenoid valve coils. (See page 5 Chapter 6.1.2 Annex 2 to HR-1 of PIC-LB-0-AN-0060-ASPI). In addition, the arm plugs for both thruster valves would have to be installed to provide a path for power. Moreover, during filling operations, the spacecraft cannot be powered because the spacecraft battery and the Ground Support Equipment are not electrically connected to the spacecraft power bus.

* - Expected conditions

Appendix C – CALIPSO Fault Tree Mitigation Matrix
Leakage of Thruster Flow Valve

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
2-0	**Failure to contain N2H4 due to Defective Valve Assembly**		
2-0-1	**Procedural Errors in assembly occur**		Refer to NESC-R-007 and NESC-R-008.
2-0-1-1	Seams that should be welded are missed		
2-0-1-2	Welding performed on seams is defective		
2-01-3	Material applied to create seals is applied incorrectly		
2-0-1-4	**Use of defective material**		
2-0-1-4-1	Use of defective material for metallic welded envelope		
2-0-1-4-2	Use of defective material for outer casing		
2-0-1-5	Critical bolts or screws are improperly torqued		
2-0-1-6	**Defective assembly of internal mechanism**		
2-0-1-6-1	Particles lodge between Armature-poppet Assembly and Seat		
2-0-1-6-2	Valve Seal is improperly formed		
2-0-1-6-3	Spring fails to close valve when power is removed		
2-0-2	**In-process Inspection Fails to Detect Assembly Errors**		Refer to NESC-R-007 and NESC-R-008.
2-0-3	**Testing Fails to Detect Leakage after Assembly**		Refer to NESC-R-003 and NESC-R-007.
2-0-3-1	**Valve Level Leak Test Fails to Detect Leakage**		
2-0-3-1-1	Valve Level Leak Test Equipment Fails		
2-0-3-1-2	Valve Level Leak Test Equipment Out of Calibration		
2-0-3-1-3	Valve Level Leak Test Procedural Error		
2-0-3-2	**Thruster Level Leak Test Fails to Detect Leakage**		
2-0-3-2-1	Thruster Level Leak Test Equipment Fails		
2-0-3-2-2	Thruster Level Leak Test Equipment Out of Calibration		
2-0-3-2-3	Thruster Level Leak Test Procedural Error		

* - Expected conditions

Appendix C – CALIPSO Fault Tree Mitigation Matrix
Leakage of Thruster Flow Valve

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
2-1	**Failure to contain N2H4: Structural Failure of Valve**		
2-1-1	**Cracks in valve propagate to critical size**		Refer to NESC-R-003 and NESC-R-007.
2-1-1-1	**Cracks, defects, or weaknesses formed in the material**		
2-1-1-1-1	Material forms cracks when machined		
2-1-1-1-2	Defective material selected for assembly		
2-1-1-1-3	Cracks or flaws formed in welds from process errors		
2-1-1-2	Stress exerted from pressure and temperature*		
2-1-2	**Structural Failure caused by Stress Corrosion Cracking**	Analysis	Materials assessment performed to preclude use of stress corrosion susceptible materials. Closed - Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1.
2-1-2-1	Material used is susceptible to Stress-Corrosion		
2-1-2-2	Stress exerted from pressure and temperature*		
2-2	**Failure to contain N2H4 due to Fluid Over-pressure**		
2-2-1	Material reacts with N2H4 due to incompatibility	Analysis	Material assessment performed to preclude use of materials incompatible with N2H4. Closed pending Aerojet compatibility test result. Reference PIC-LB-0-AN-0060-ASPI Chapter 6.1.1. Materials used are compatible with N2H4 according to MSFC-HDBK-527 rev. F.
2-2-2	**Improper filling of propulsion fuel system**		Refer to NESC-R-005.
2-2-2-1	Undetected Errors occur in Filling Procedure		
2-2-2-2	Critical GSE used for filling process fails		
2-2-2-3	Critical GSE for filling process is out of calibration		
2-3	**Failure to contain N2H4 due to physical damage**		

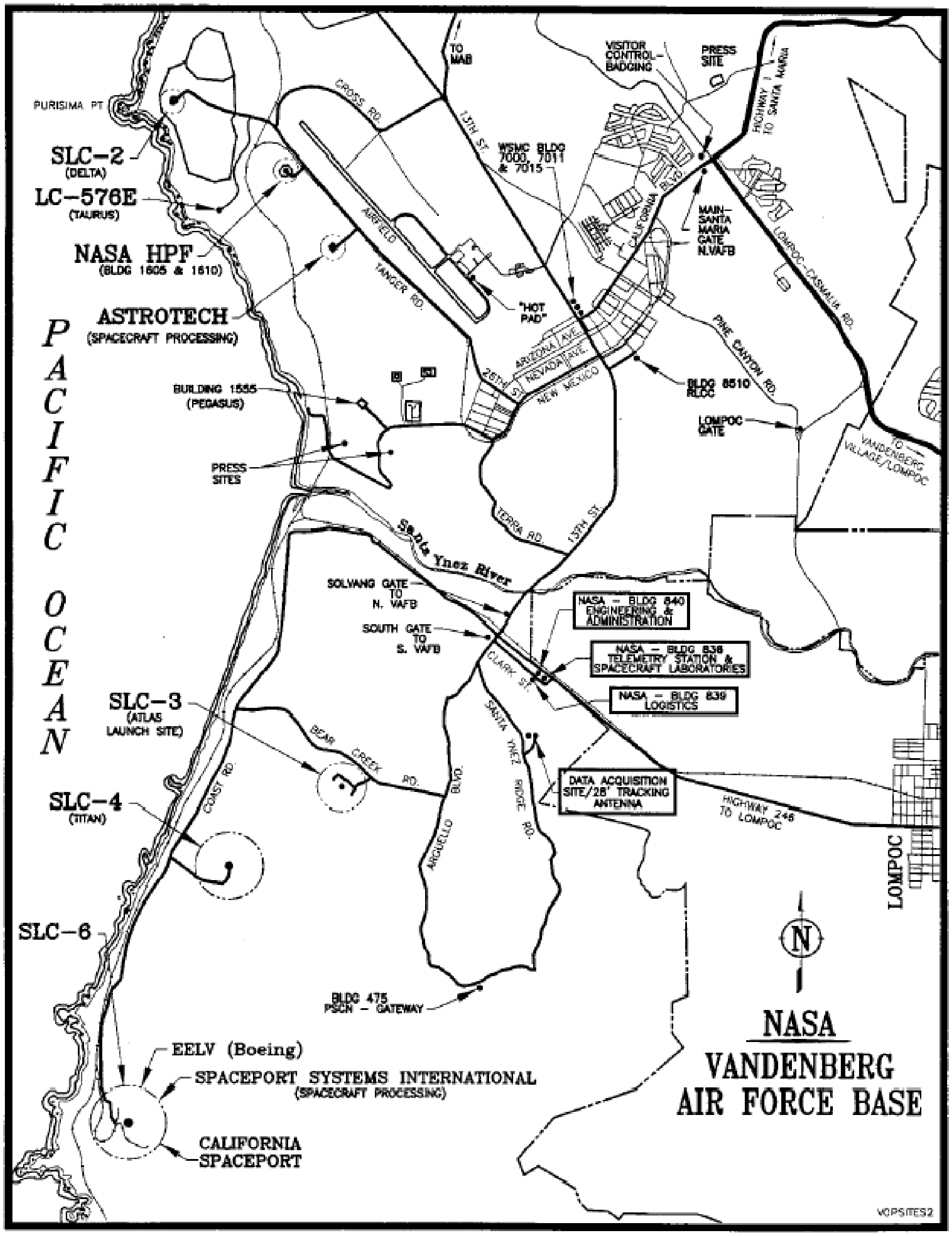
* - Expected conditions

Appendix C – CALIPSO Fault Tree Mitigation Matrix
Leakage of Thruster Flow Valve

EVENT NUMBER	EVENT DESCRIPTION	VERIF. METHOD	RECOMMENDED MITIGATION ACTION
2-3-1	**Valve seal broken by mechanical shock**		Refer to NESC-R-004.
2-3-1-1	Spacecraft dropped during processing		
2-3-1-2	Spacecraft collides with an object during processing		
2-3-2	**Valve seal broken by vibration loads**		Refer to NESC-R-004.
2-3-2-1	Vibration levels during transportation damages valve		
2-3-2-2	Vibration levels during lift and mounting of Spacecraft damages valve		
2-3-3	Valve seal broken during system assembly		Refer to NESC-R-007.
2-3-4	Valve seal broken during system test		
2-3-5	Valve seal broken during maintenance action		
2-4	**Failure to contain N2H4 due to Temperature Changes**	Analysis/ Inspection	Spacecraft temperature controlled to small variations during ground processing. Closed - Reference Launch Vehicle ICD MDC-01H0074.
2-4-1	Materials used have significantly different Coefficients of Thermal Expansion		
2-4-2	Temperature variations/cycling occurs*		

* - Expected conditions

Appendix D. VAFB Site Map



Aerojet CALIPSO Test Plan

A02026.11

January 9, 2004

Aerojet Evaluation Team

- Dr. Scott Miller, Manager - Systems and Bipropellant Technology
- Jack DeBoer, Staff Engineer
- Patrick Cabral, Development Engineer

Aerojet Test Plan Summary

- **Mechanical Fitting Evaluation Objectives**
  - **Simulate both valve (CRES male inlet fitting to titanium flared tube) and tank (titanium male inlet fitting to titanium flared tube) fitting configurations to the best fidelity possible given available CALIPSO information**
  - **Perform hydrazine soak test simulating pre-launch loaded system duration to assess effect of hydrazine on nickel seal material**

Aerojet Test Plan Summary (Cont'd)

- **Hot Soak Test of Nickel Seals**
  - **Place qty 16 nickel seals in hydrazine for parallel exposure test on nickel material only. Volume of hydrazine and seal quantity is outlined below.**

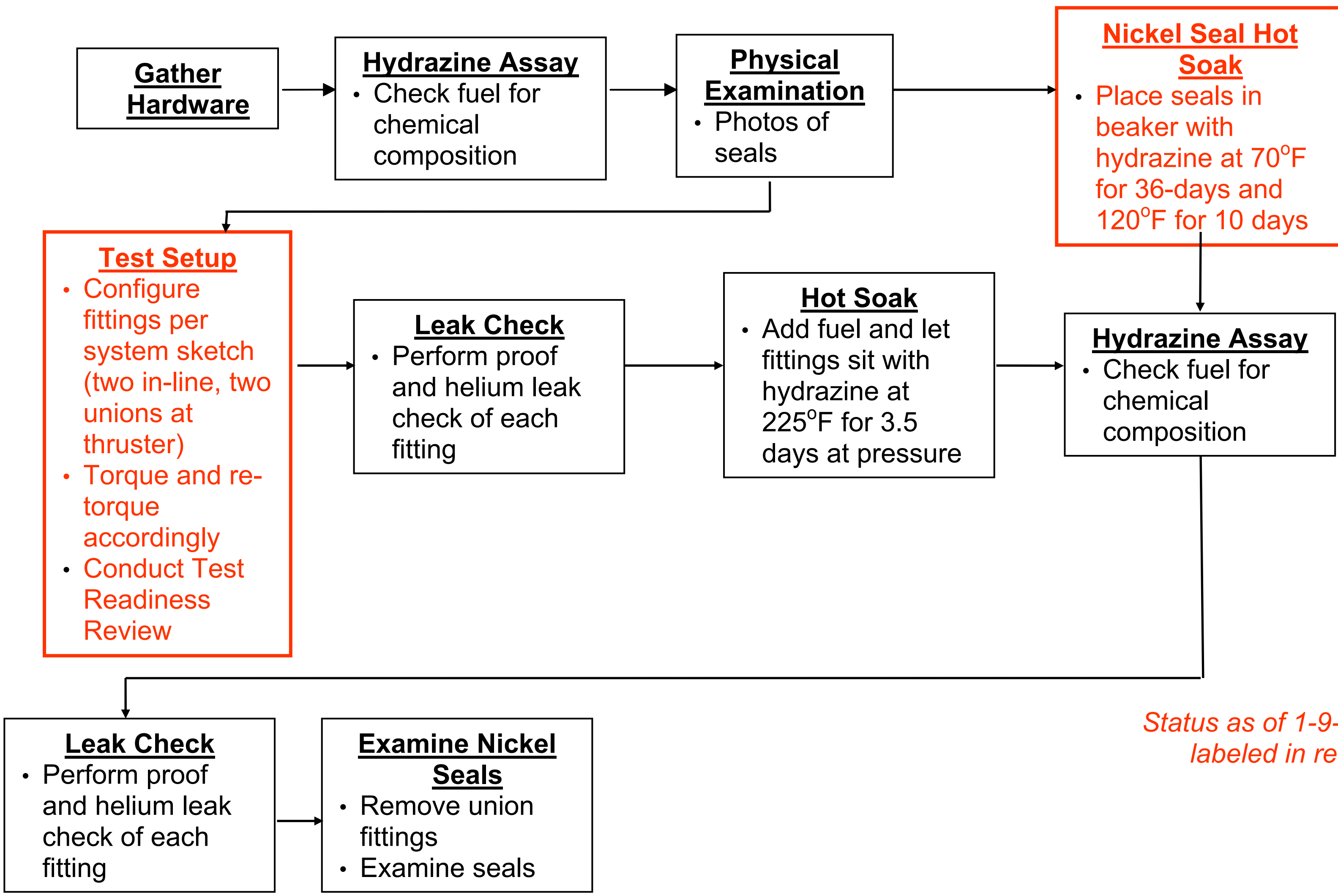
Sample Description	Volume of Hydrazine	QTY of Seals	Test Duration	Temperature
Control	50 mL	0	36-days	Ambient
Fitting Exposure	50 mL	5	36-days	Ambient
Fitting Exposure at Elevated Temperature	50 mL	5	10-days	$120^{o}F$
One Seal Exposure	50 mL	1	36-days	Ambient
Fitting Exposure with Weekly Check	100 mL	5	36-days	Ambient

  - **Perform hydrazine assays before and after testing on all samples; Weekly tests performed on 100 mL for duration of test**
  - **Success criteria for post-test assays (nickel ppm and gas evolution rate) to be discussed by team when results are available**

Aerojet Test Plan Summary (Cont'd)

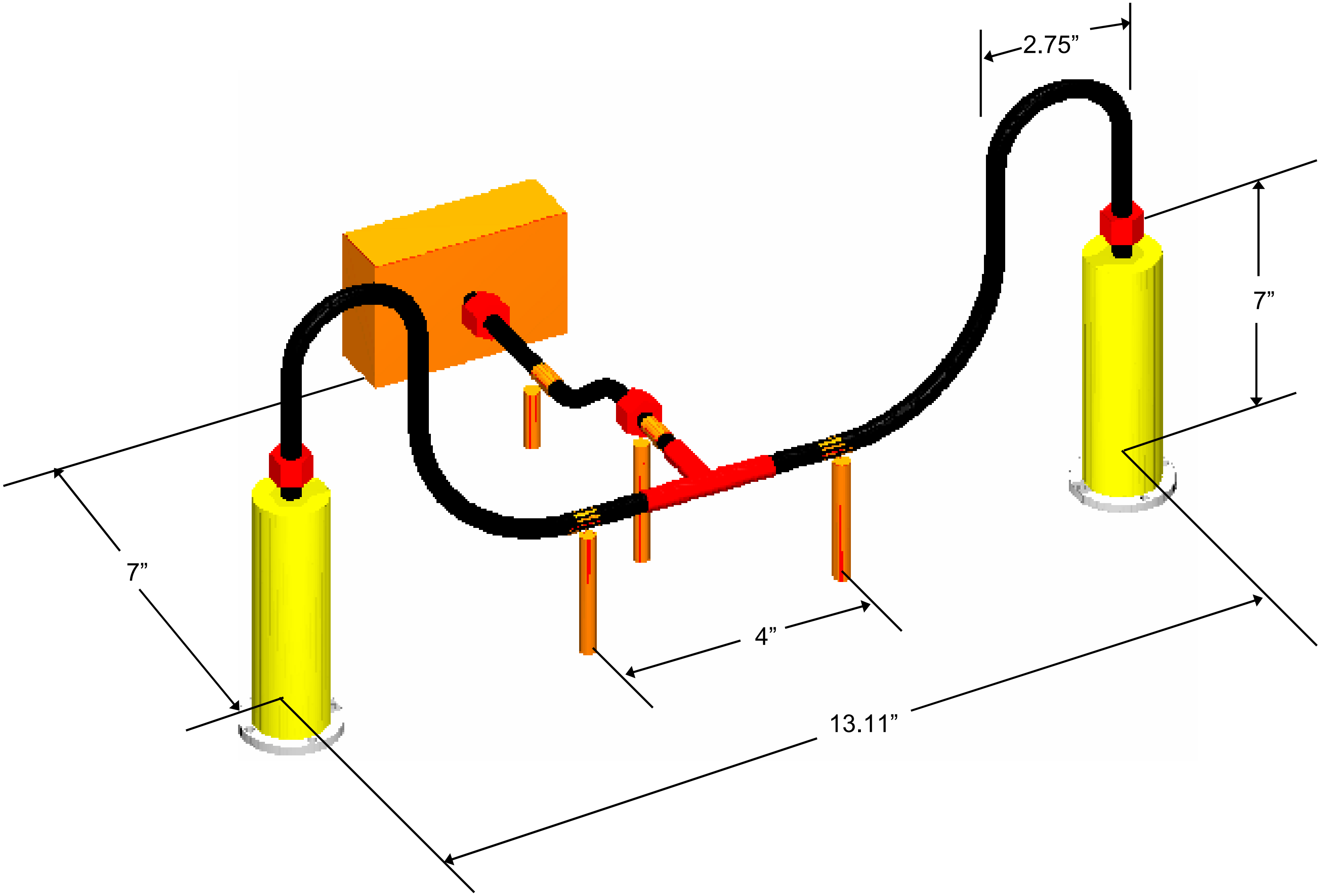
- **Hot Soak Test of Test Hardware**
  - Obtain flight-like mechanical fittings (MS33656-4). CRES and titanium fittings are available.
  - Prepare test hardware approximating portion of CALIPSO system (fittings + tubing) using representative tubing material and lengths, and assembled according to CALIPSO procedures
  - Torque fittings to 100% flight torque (including re-tightening schedule), apply torque stripe
  - Proof test at 480 psig (1.5 x MEOP)
  - GHe leak test at 320 psig (MEOP)
  - Load test hardware with N2H4, perform accelerated exposure test representative of 36 days duration in Aerojet sea level test chamber (225F for 3.5 days)
  - Obtain pre- and post-exposure N2H4 samples, perform assays
  - Decontaminate, repeat proof and GHe leak tests
  - Check torque strength of unions at thruster location by ensuring it is greater than or equal to original torque value
  - Undo thruster fitting and examine nickel seals
  - Examine seals to determine surface effects of nickel and hydrazine interaction. Distribute results of seals to team for evaluation and further direction. Success criteria for post-test assays (nickel ppm and gas evolution rate) to be discussed by team.

Aerojet Test Plan Summary (Cont'd)



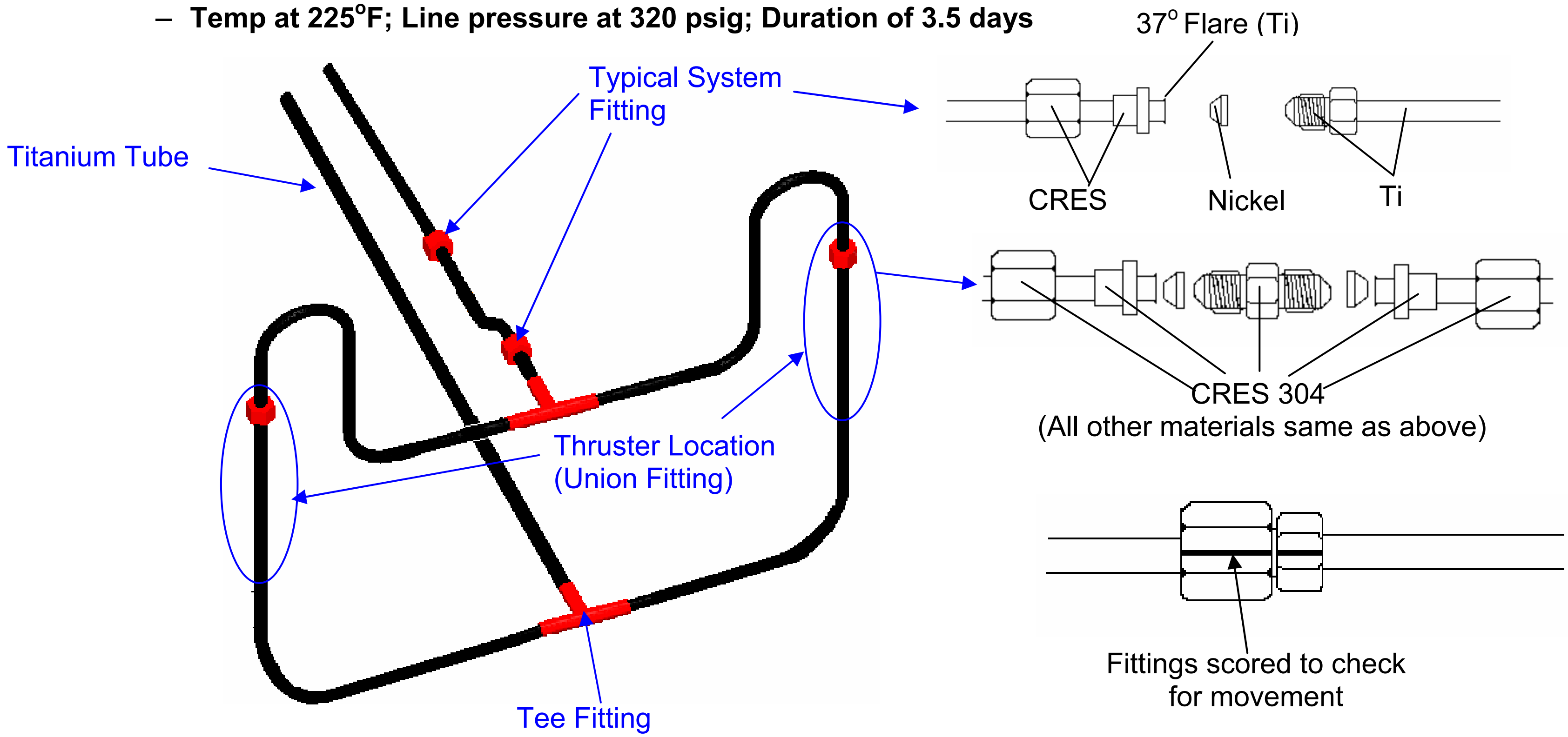
Status as of 1-9-2004 labeled in red

Propulsion System Schematic for Test

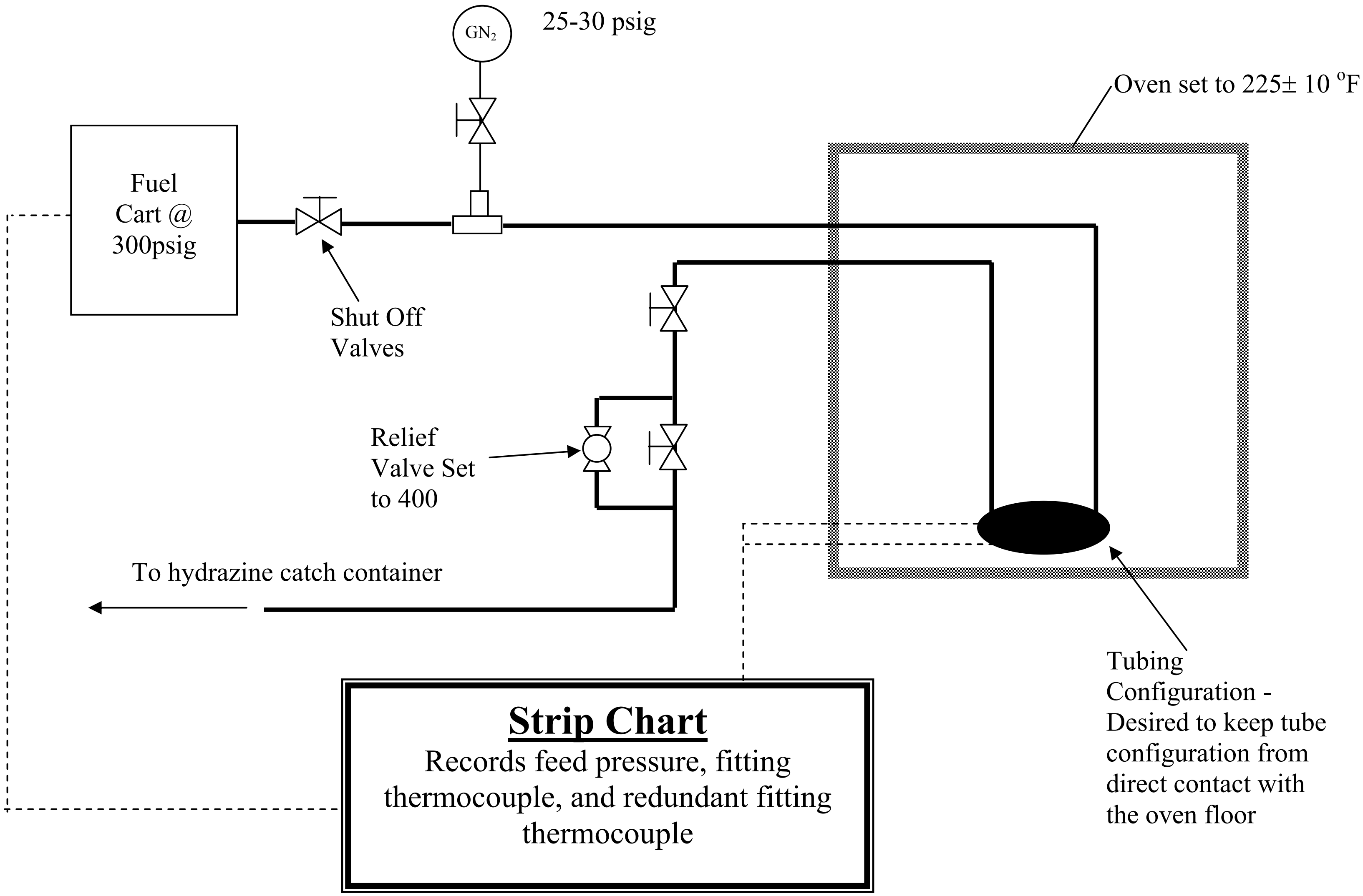


Hot Soak Test Setup

- **Four fittings to be tested: Two in titanium line, and two CRES at thruster location**
  - **Thruster fittings simulated for hot soak test due to the uncertainty of the valves acquired. Valves need to function properly when exposed to hydrazine for decontamination purposes.**
- **Lines filled with hydrazine and stored in oven**
  - **Temp at 225°F; Line pressure at 320 psig; Duration of 3.5 days**



Hot Soak Test Facility



Aerojet Test Plan Summary (Cont'd)

Hydrazine Compatibility Test

- **Sample of hydrazine before and after hot soak, and for ambient test in chemistry lab**
  - **Trace metals test**
    - **Inductively Coupled Plasma (ICP) technique used**
      - **Nickel levels to 1 ppm**
      - **All other metals down to ppb**

Aerojet Test Plan Summary (Cont’d)


Pressure consoles


Helium leak detector


Test Stand/Vacuum chamber

Proof/Leak Testing

- **Proof test at 1.5 X 320 psig**
  - **Test hardware will be capped on one end and pressurized with GN2. Fitting will be snooped to check for leaks**
  - **GP-TE-016 High Pressure Console to control pressure input**
- **Helium Leak Check**
  - **Fittings tested for leaks at 320 psig with GHe via “bag” isolation and mass spectrometer**
  - **GP-TE-002 Test Stand Bay to control pressure input**
  - **Mass Spectrometer (Varian Turbo Auto-Test 947)**
    - **Integrity >= 1X10^{-8} scc/sec. (1x10^{-6} scc/sec. typical max allowable for acceptance of rocket engines)**

Aerojet Test Plan Summary (Cont'd)

- Mechanical Fitting Evaluation - Schedule and Status
  - Obtain all required information or proceed based on assumptions: Complete
  - Gather materials: Complete
  - Prepare and review test plan: Complete
  - Conduct Test Readiness Review: 1/9
  - Prepare hot soak test setup: 1/9-1/12
  - Hydrazine exposure (Hot Soak Test): 1/12 - 1/17
  - Hydrazine exposure (Ambient Test Nickel Seals Only): 1/9 - 2/16
  - Hydrazine exposure (120°F Test Nickel Seals Only): 1/12 - 1/23
  - Final examination and analysis (Hot Soak Test): 1/19
  - Final examination and analysis (Ambient Test Nickel Seals Only): 2/16 - 2/17
  - Final examination and analysis (120°F Test Nickel Seals Only): 1/23-1/24

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14. ABSTRACT
CALIPSO is a joint science mission between the CNES, LaRC and GSFC. It was selected as an Earth System Science Pathfinder satellite mission in December 1998 to address the role of clouds and aerosols in the Earth's radiation budget. The spacecraft includes a NASA light detecting and ranging (LIDAR) instrument, a NASA wide-field camera and a CNES imaging infrared radiometer. The scope of this effort was a review of the Proteus propulsion bus design and an assessment of the potential for personnel exposure to hydrazine propellant.

15. SUBJECT TERMS
Spacecraft design; Propulsion systems; Thrust control devices; Hydrazine propellants; Launch facilities; CALIPSO

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